Neutrino astronomy and neutrino physics with KM3NeT

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Particle Physics Colloquium, University of Heidelberg
21 June 2016

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PHYSICS

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The plan for the next 45+ minutes

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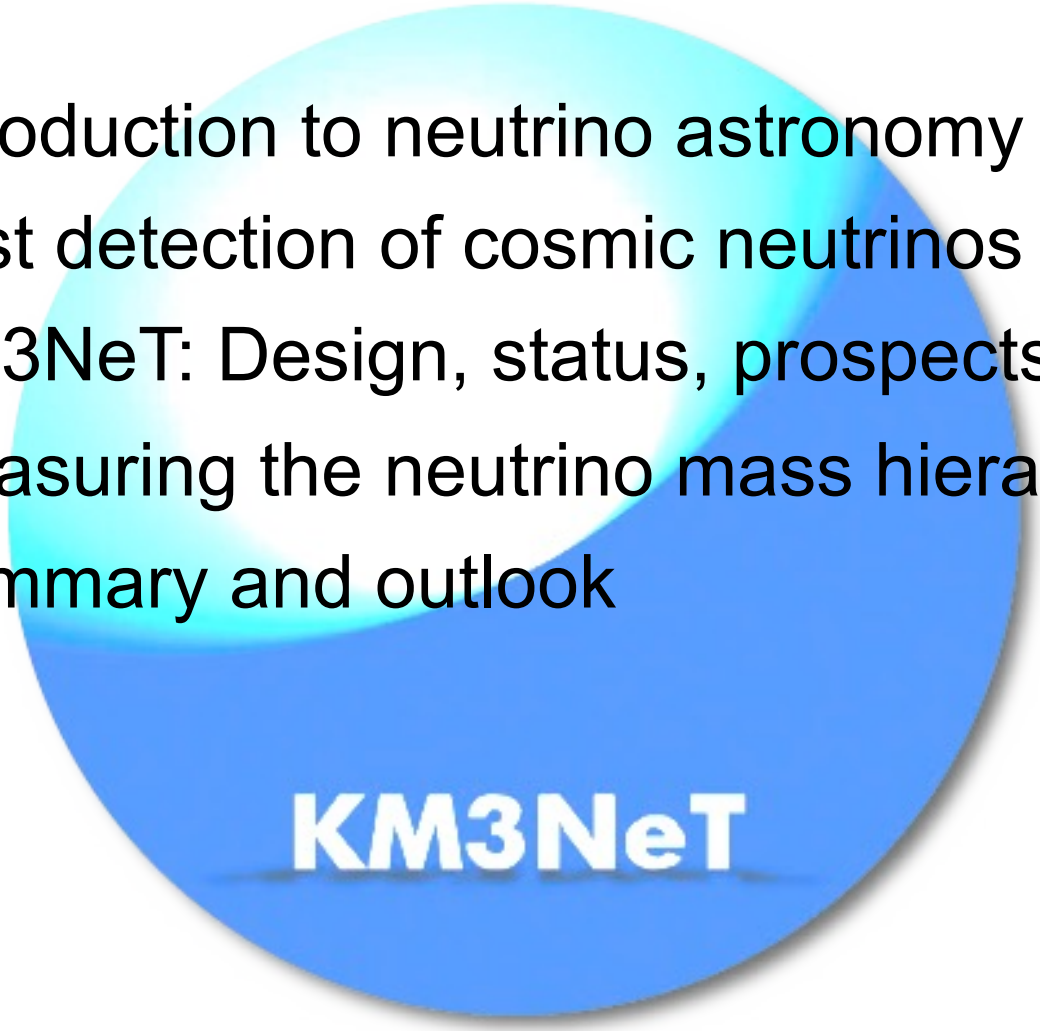
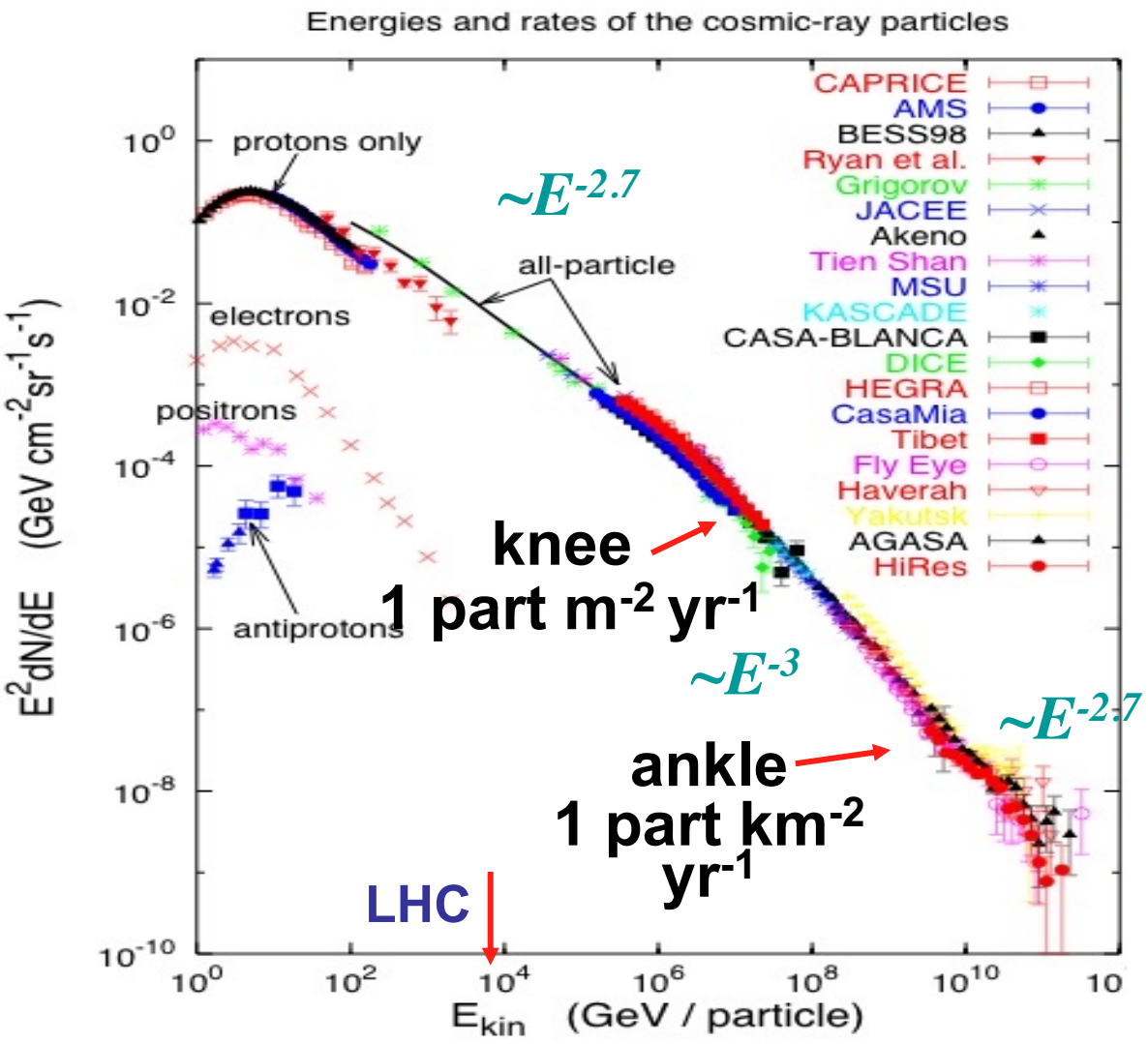
- Introduction to neutrino astronomy
- First detection of cosmic neutrinos with IceCube
- KM3NeT: Design, status, prospects
- Measuring the neutrino mass hierarchy
- Summary and outlook



Neutrino astronomy

The mysterious cosmic rays



- Particles impinging on Earth from outer space carry energies up to 10^{21} eV (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.

Neutrino production mechanism

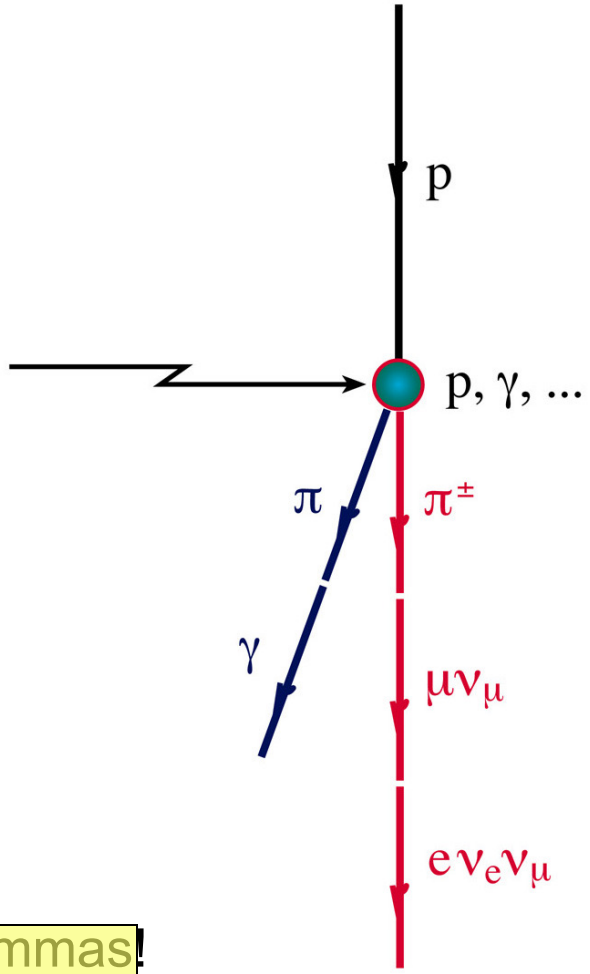
- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}...) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

Cosmic rays

$$\downarrow$$

$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$



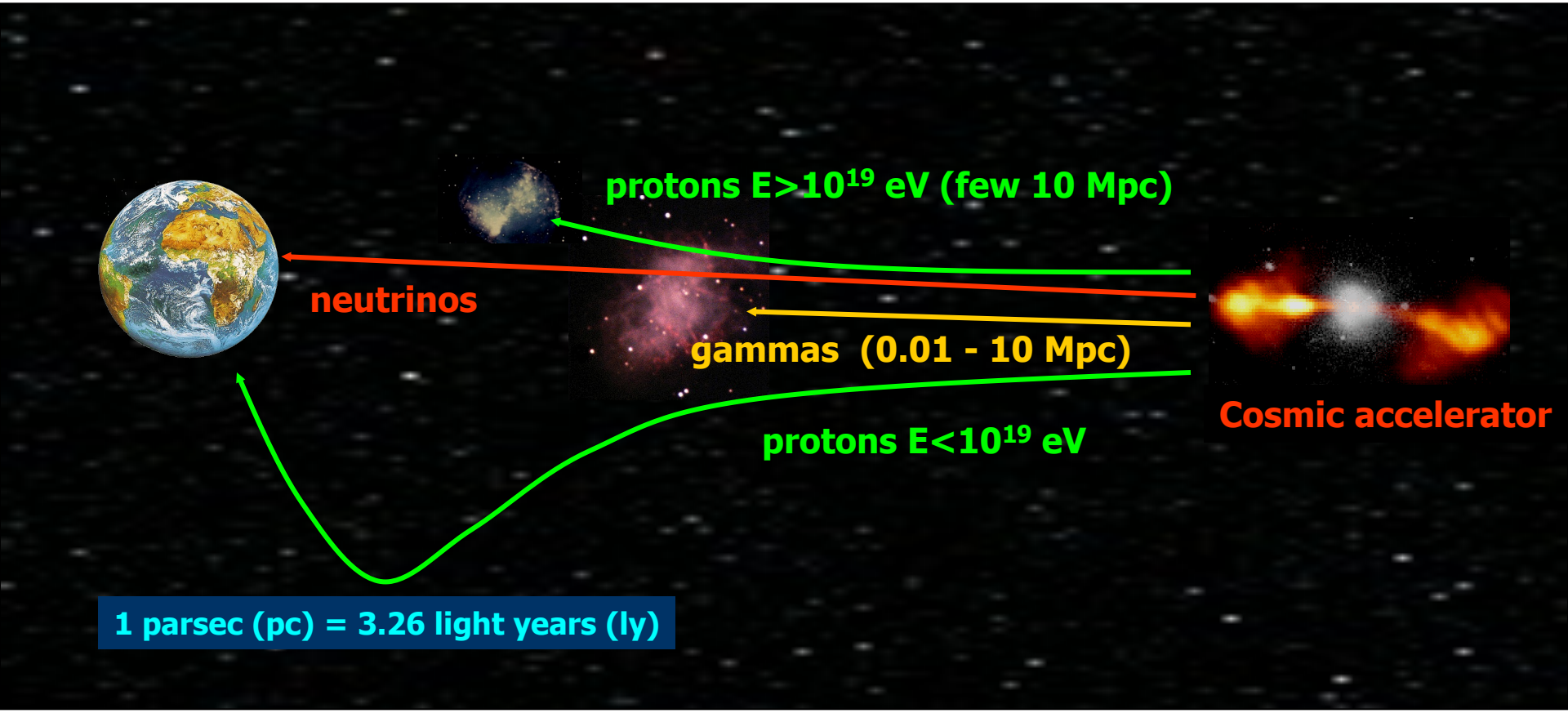
- Simultaneously, gamma production takes place:

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\ \gamma + Y$$

Cosmic rays

- Cosmic ray acceleration yields neutrinos and gammas!
- … but gammas also from purely leptonic processes

Particle propagation in the Universe



Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

How does a neutrino telescope work?

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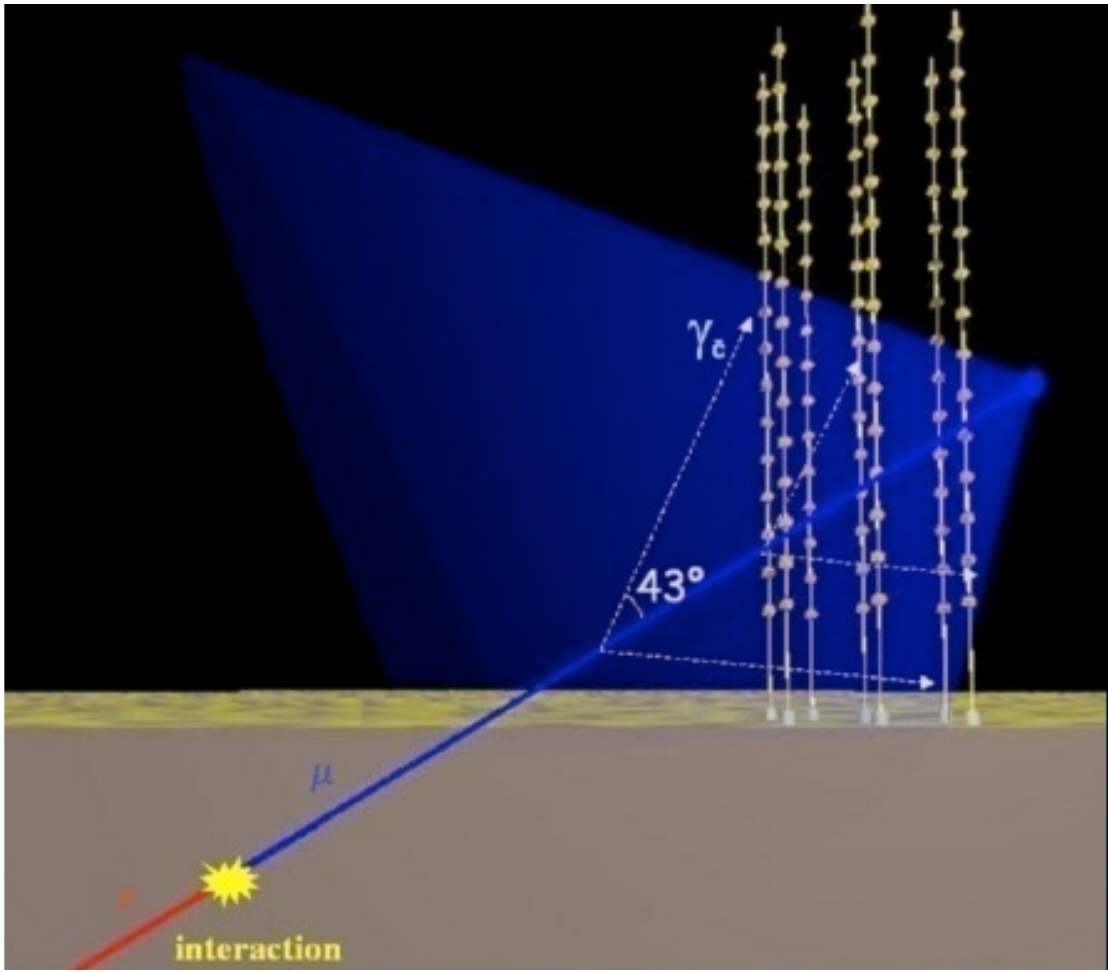
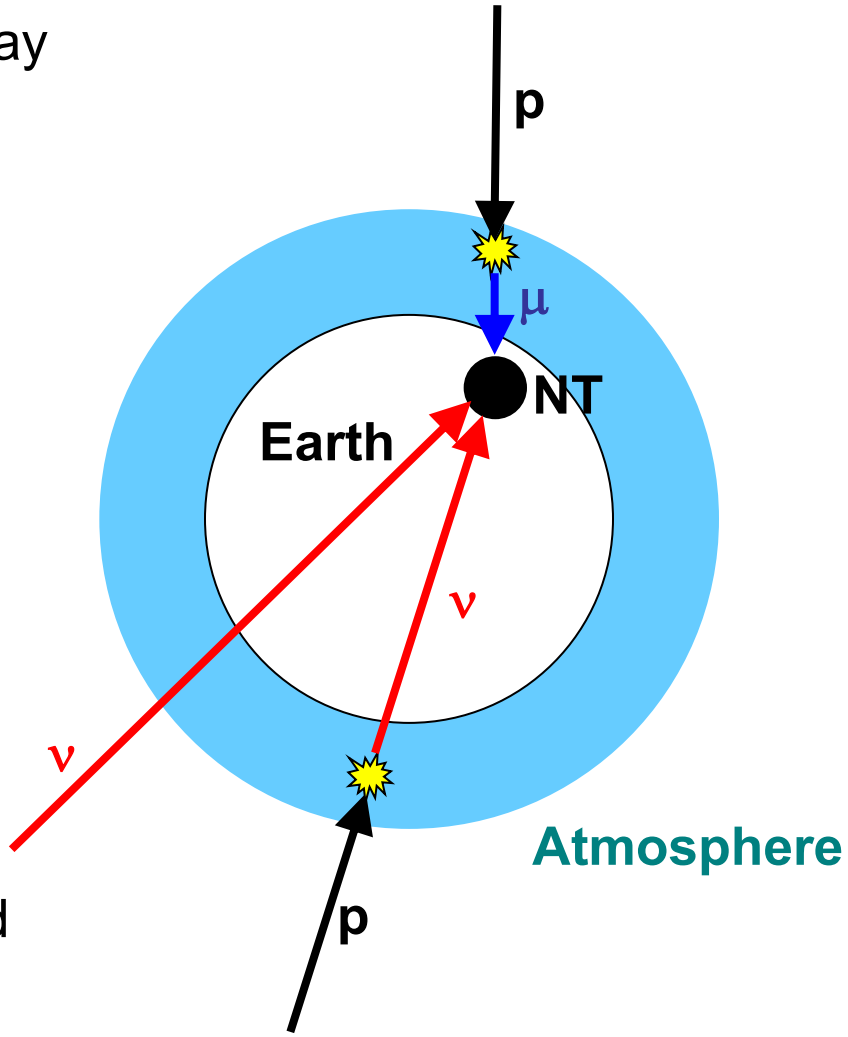
- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission
- Recorded by a 3D-array of photo-sensors
- “Traditional” channel:
  $\nu_\mu + N \rightarrow \mu + X$
- Energy range :
  10(0) GeV – some PeV



Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Sea water: light from K40 decays and bioluminescence



The ν telescope world map

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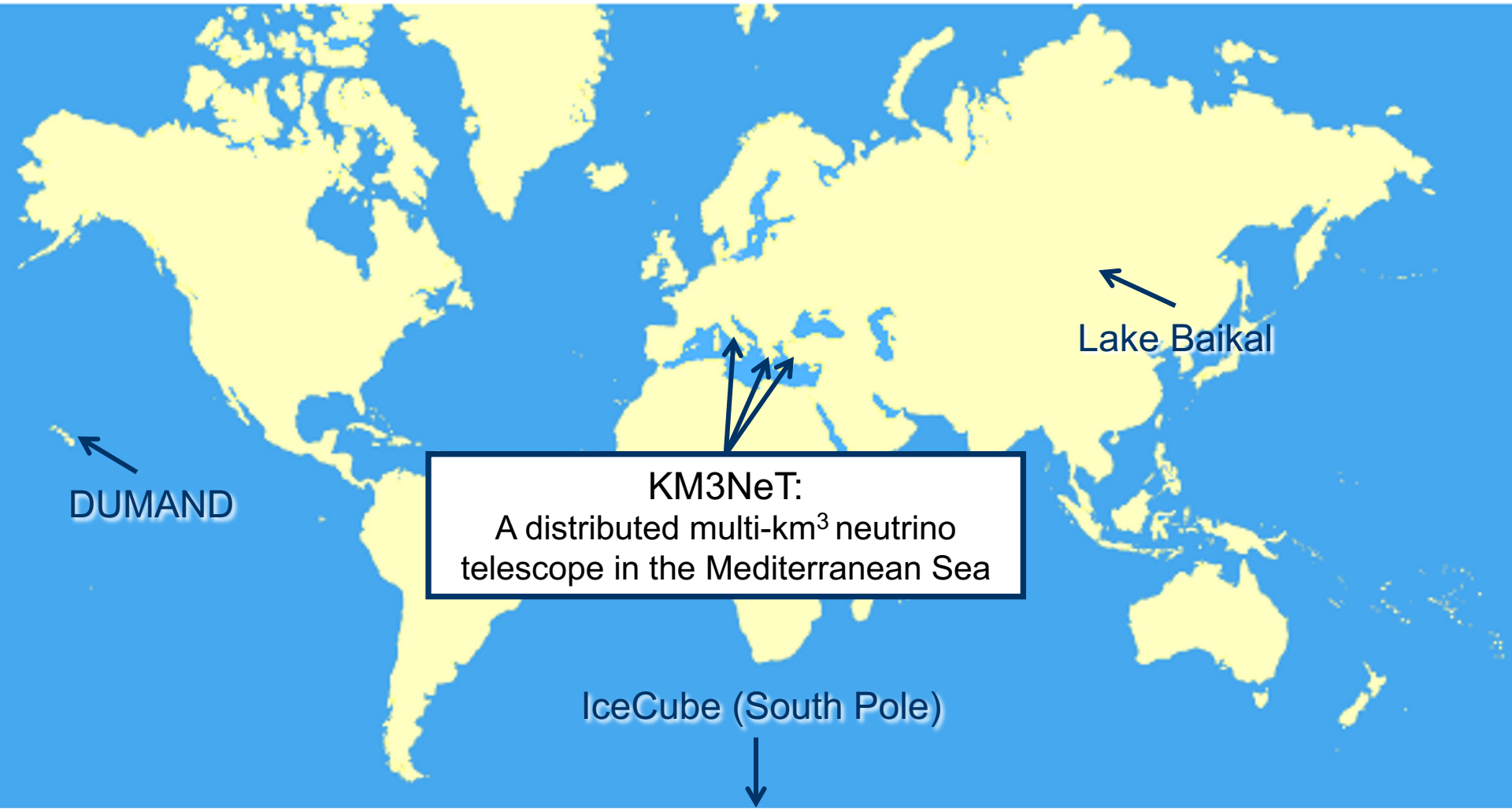
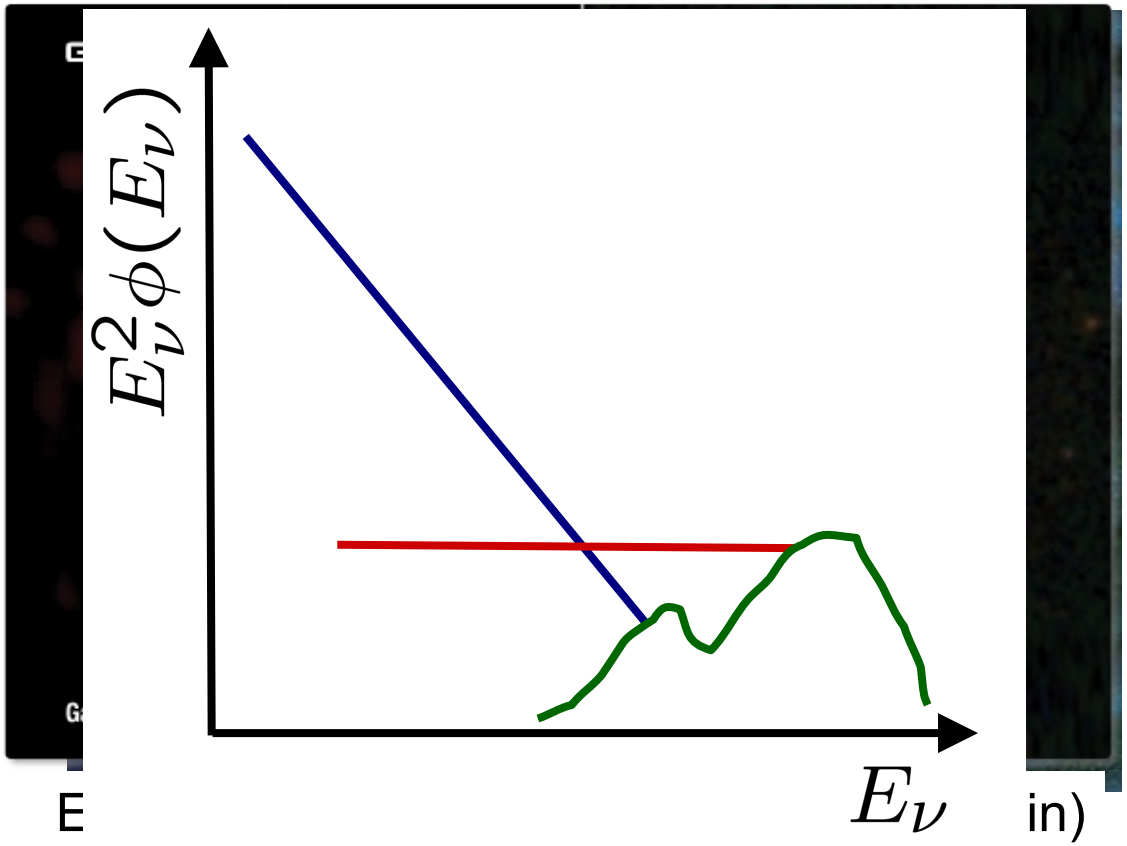


Example targets of ν astronomy

- Galactic neutrino sources
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux
- Neutrinos from Dark Matter annihilations
- Particle physics with atmospheric neutrinos
- Search for exotics (monopoles, nuclearites,…)



Isotropic high-energy neutrino flux above atmospheric neutrino background from unresolved astrophysical sources or of cosmogenic origin (GZK)

South Pole and Mediterranean Fields of View

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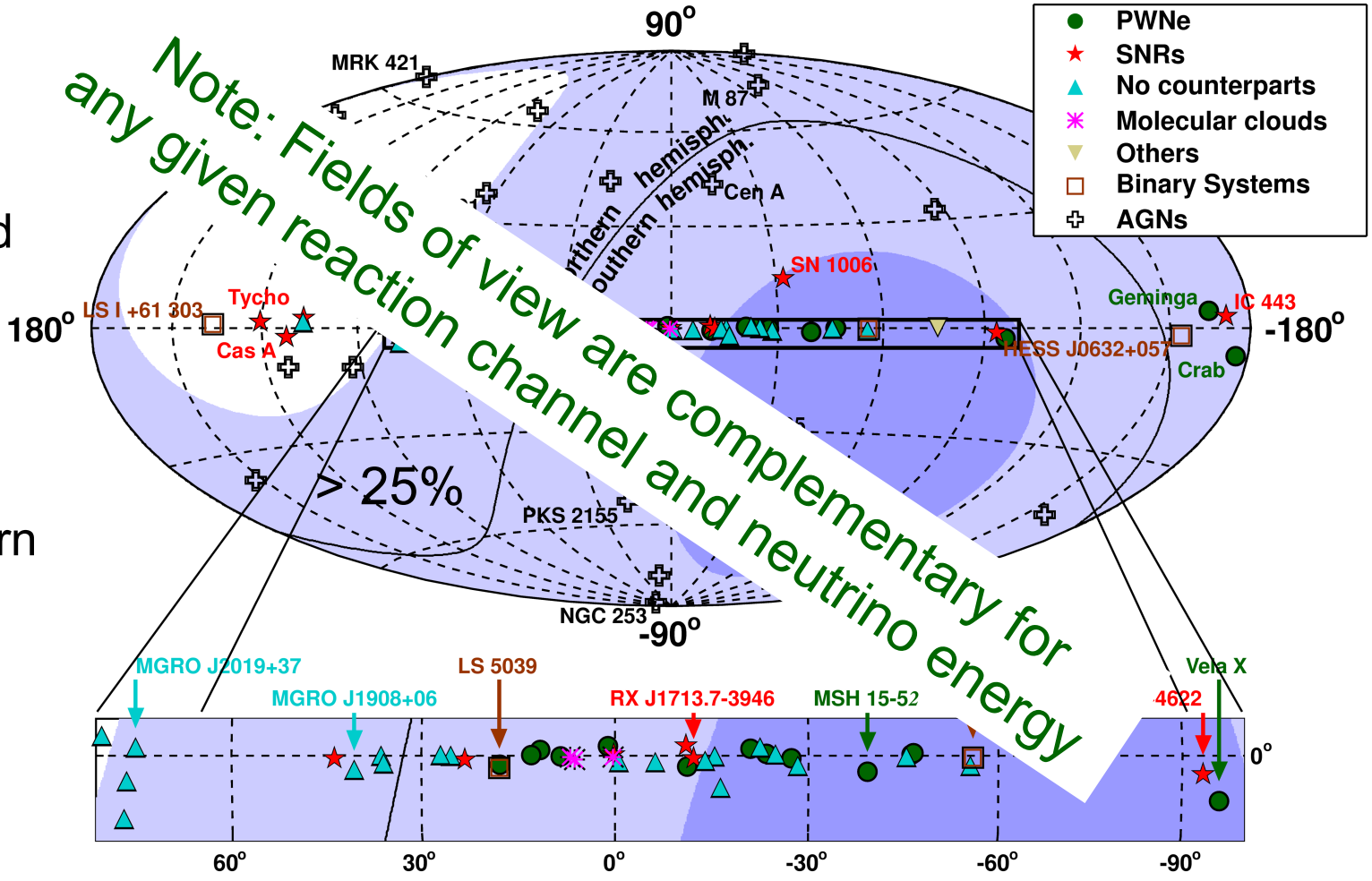
Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere



IceCube and the first detection of cosmic neutrinos

Several slides adapted from:
F. Halzen: “IceCube: the discovery of cosmic neutrinos”, VHEPA 2016
K. Hanson: “IceCube Gen2”, VHEPA 2016

IceCube: A km^3 detector in the Antarctic ice

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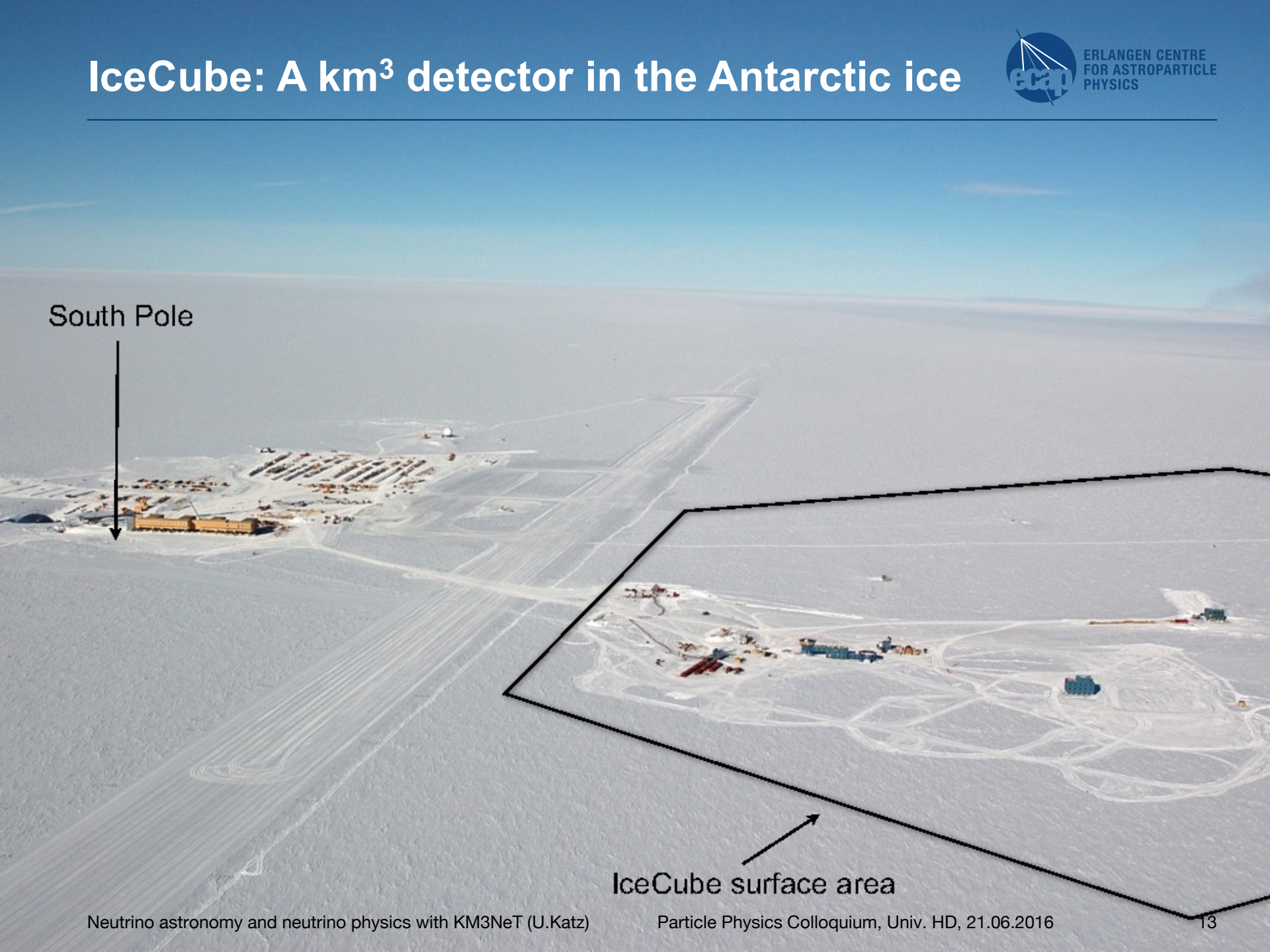
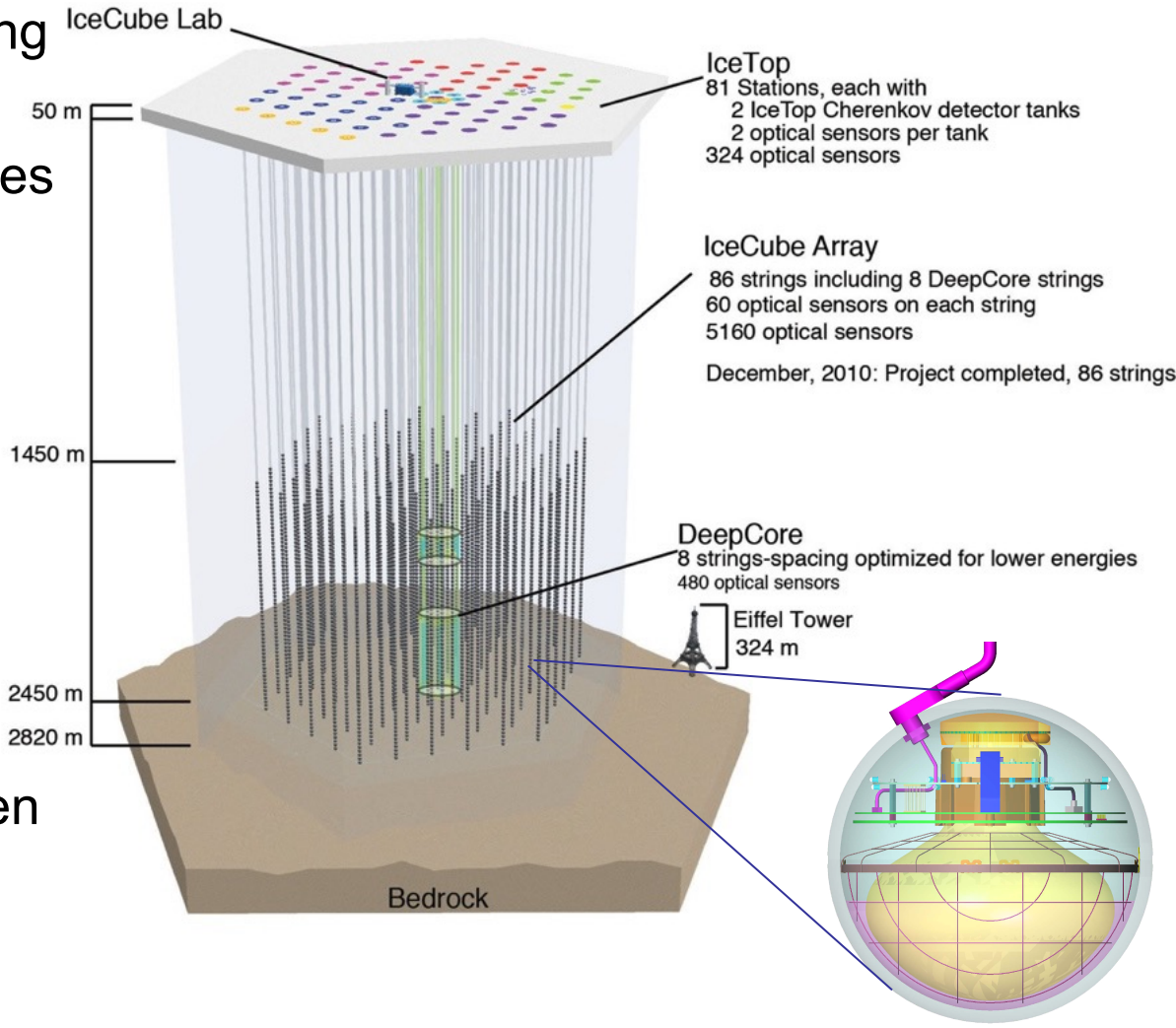
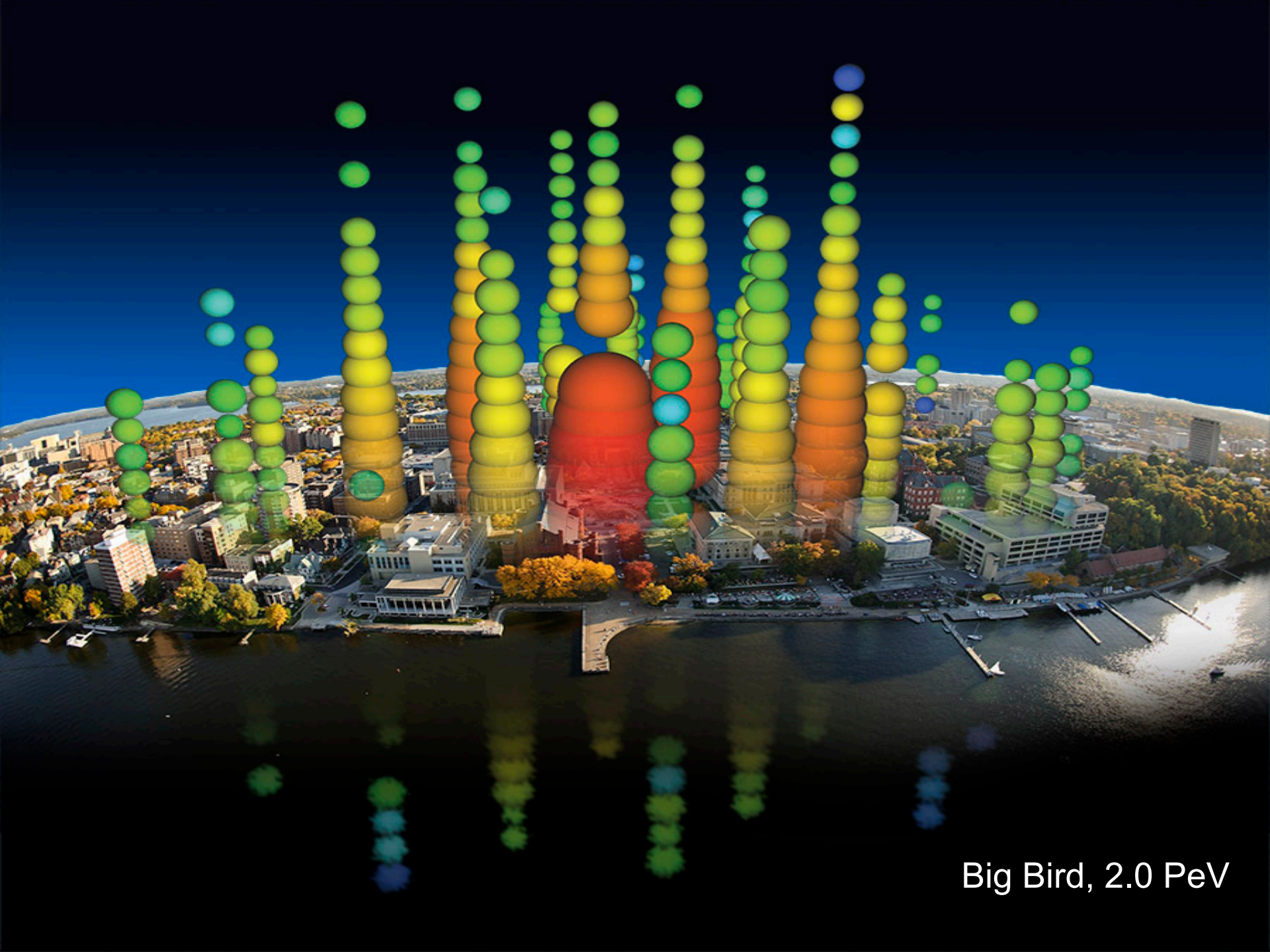


The IceCube detector

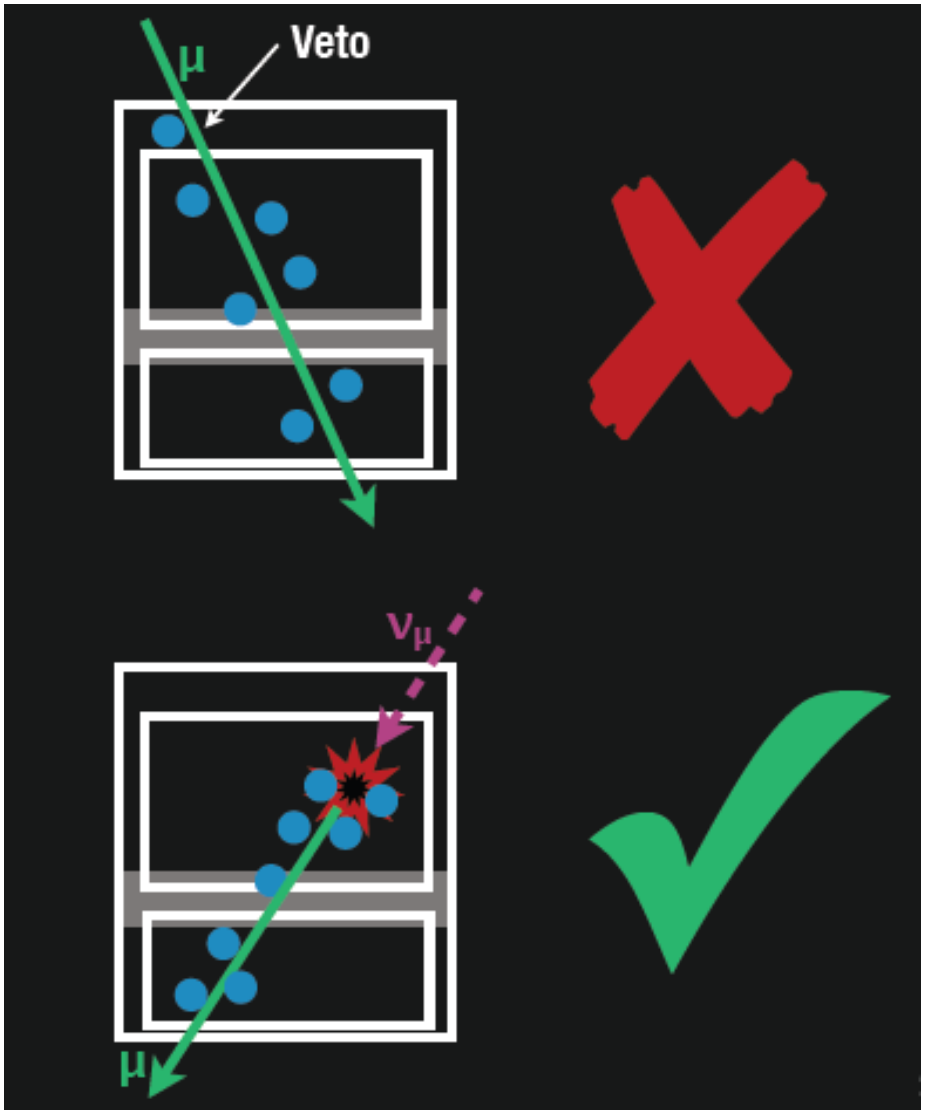
- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km^3 instrumented volume, depth 2450m
- Deep Core
  - densely instrumented region in clearest ice
- Completed in Dec. 2010
- Extremely stable and efficient operation since then



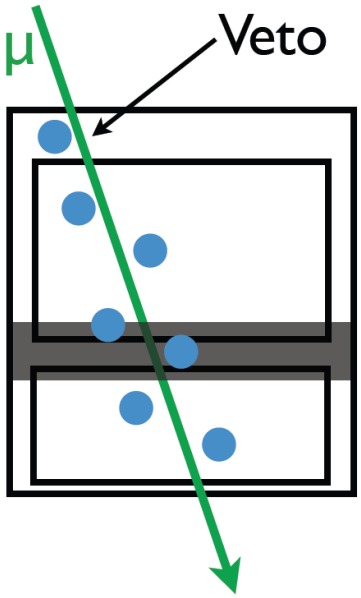

Big Bird, 2.0 PeV

Systematic search for such events …

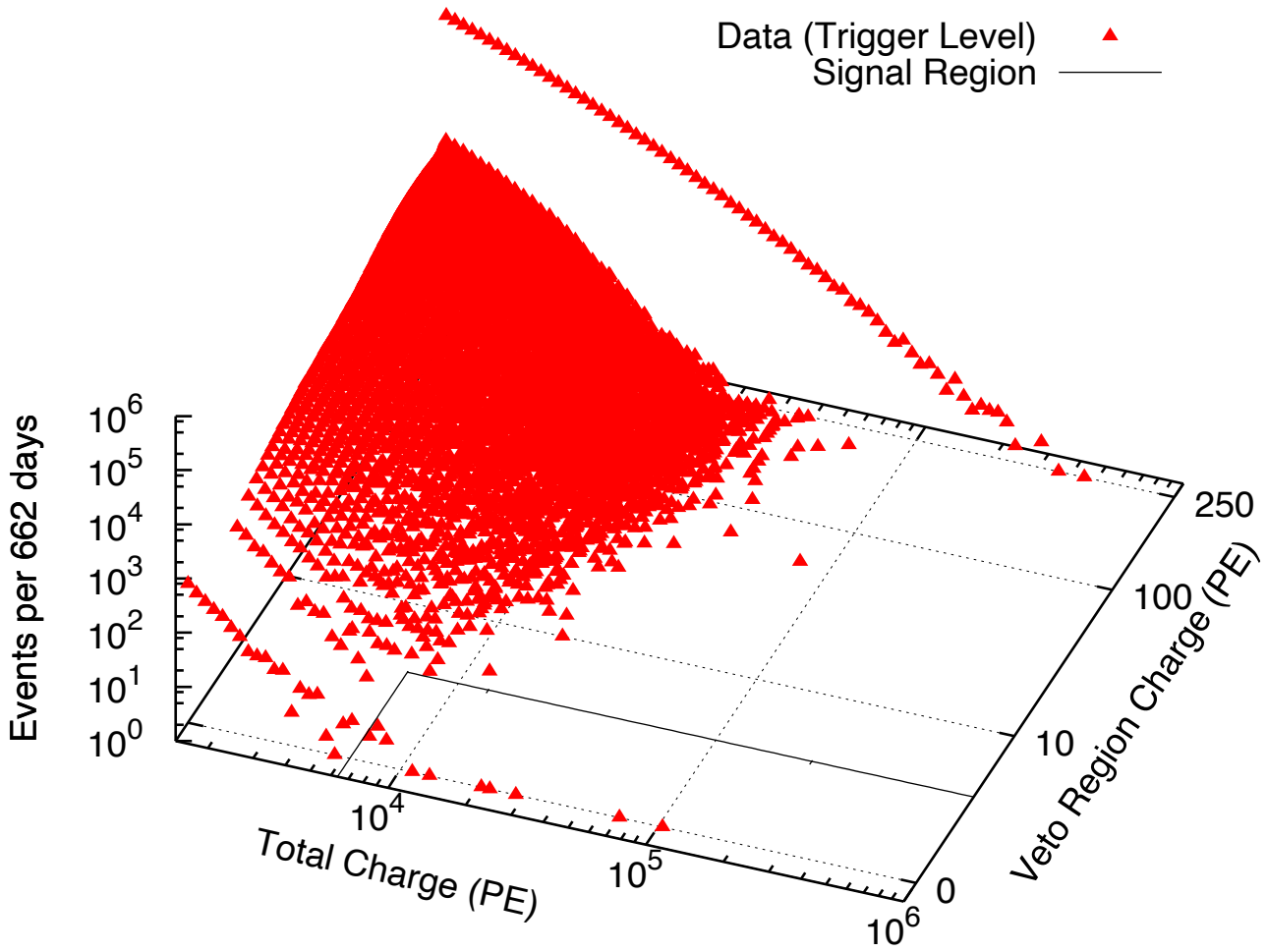
- Select events interacting inside the detector only
- No light in the veto region
- Veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- Energy measurement: total absorption calorimetry
- → “High-energy starting events” (HESE)
- Meanwhile further analyses



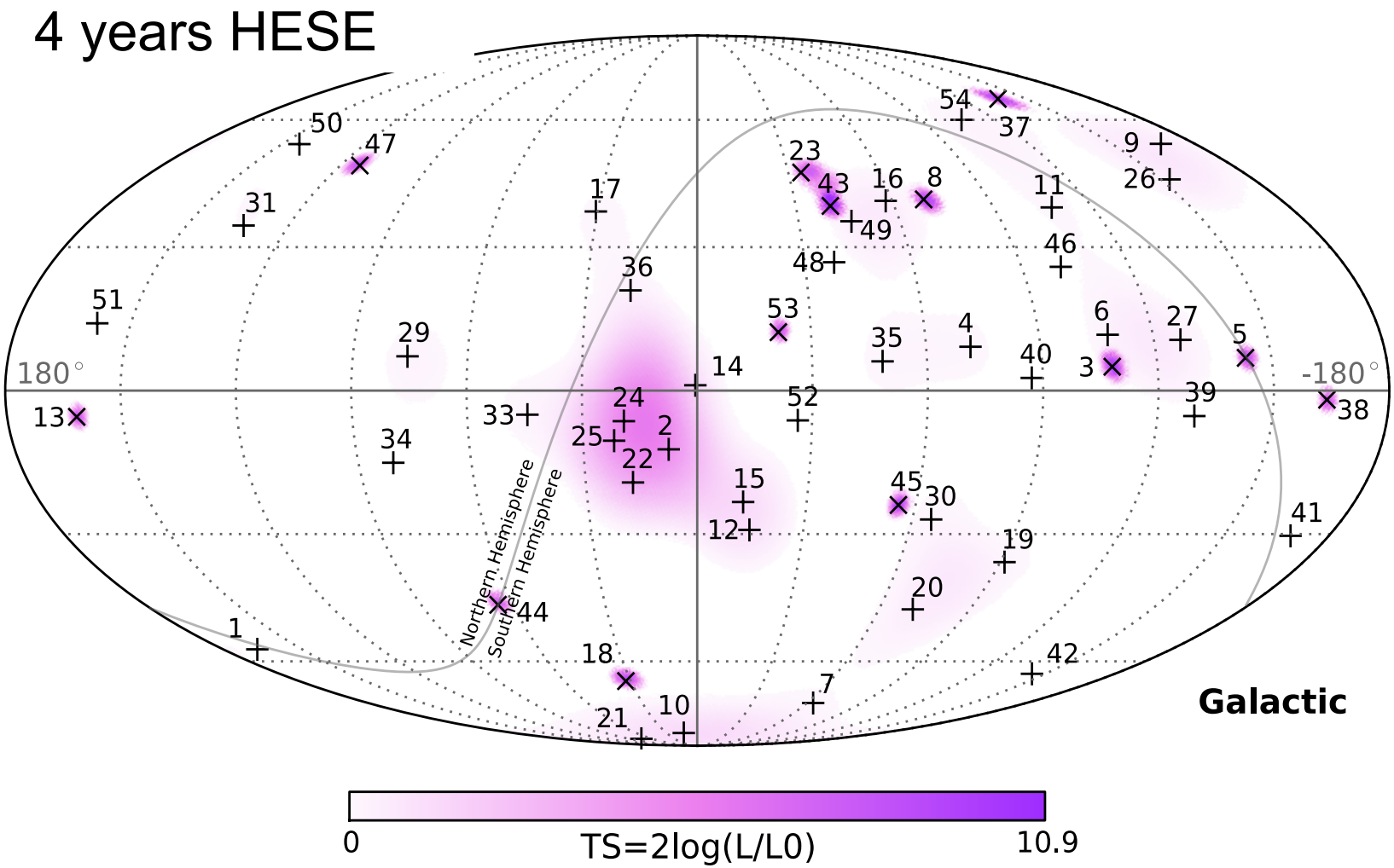
… success!



26 events in one year of data!

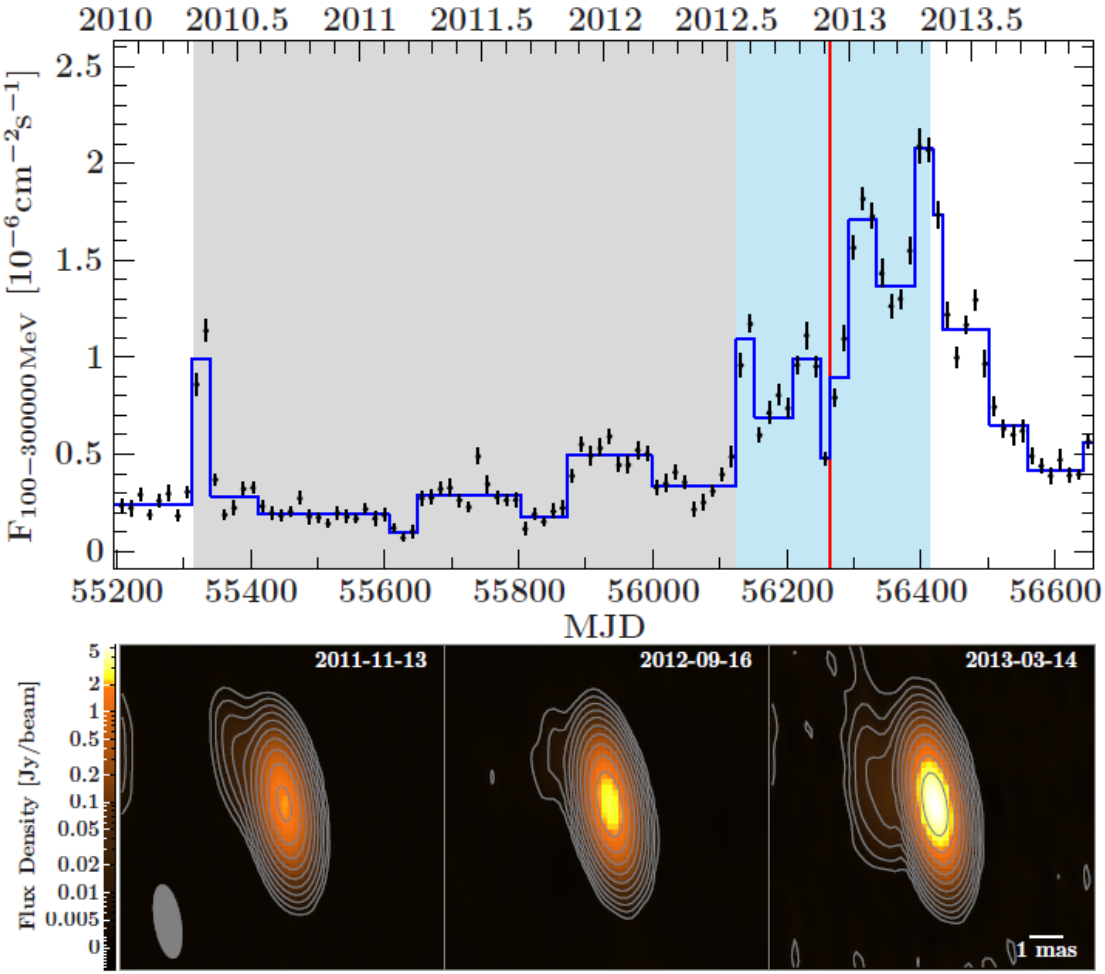


Where do they come from?



IceCube events from blazars?

- Multi-messenger analysis using Fermi-LAT and radio data
- Candidate source for Big Bird: “Flat-spectrum radio quasar (FSRQ)” B1424-418 – temporally and spatially coincident
- Consistent with astrophysical modelling
- Probability for random association 5%



M. Kadler et al., arXiv:1602.02012
to appear in Nature Physics

And now?

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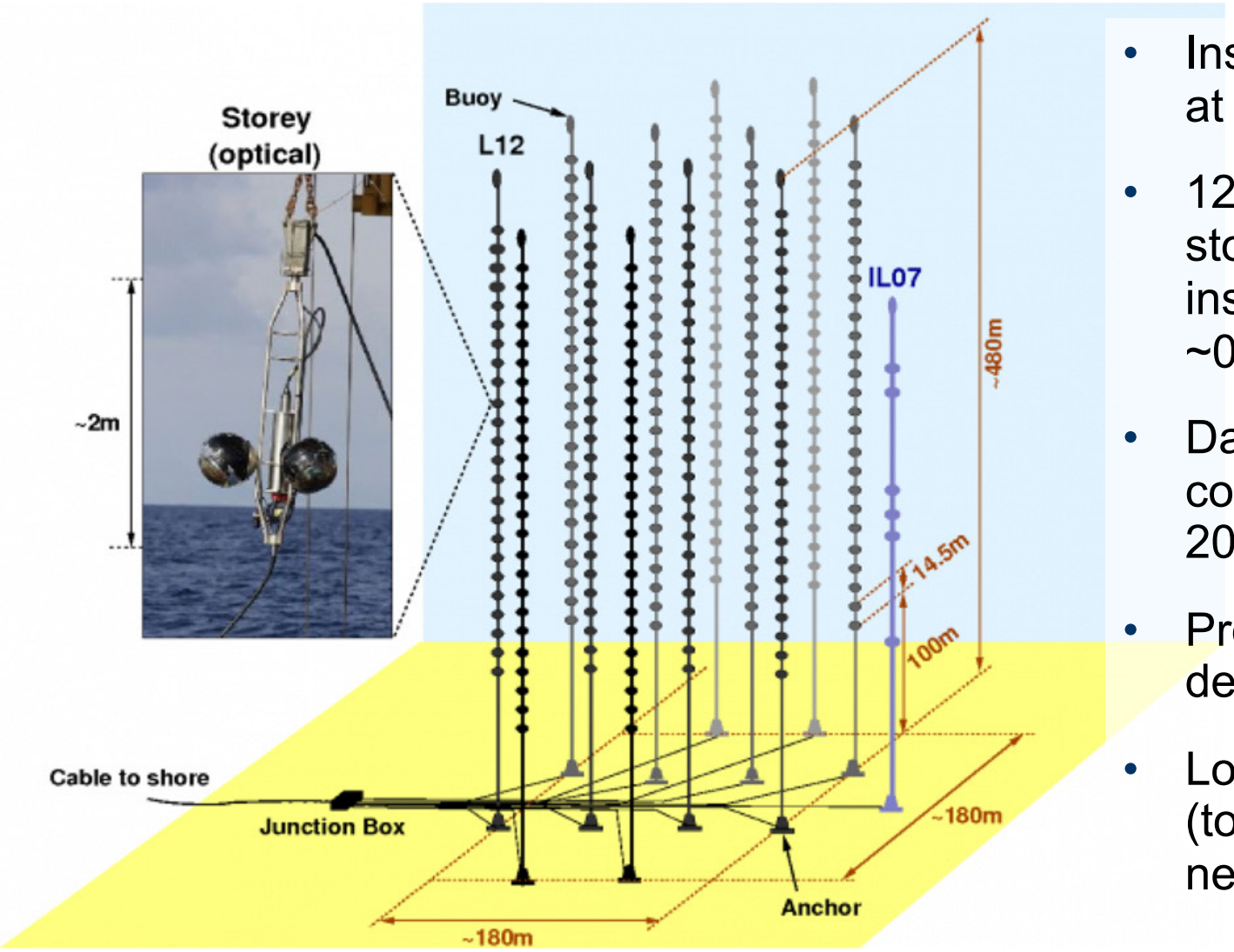
- More data needed to draw firm conclusions!
- Future projects: KM3NeT and IceCube-Gen2

- KM3NeT-ORCA:
  Dense array, ν physics
  Construction 2017-
- KM3NeT-ARCA:
  High-energy ν telescope
  Construction 2018-

- PINGU:
  Dense array, ν physics
  Construction 2021-
- Gen2-HEX:
  High-energy ν telescope
  Surface array
  Radio array ?
  Construction 2025-

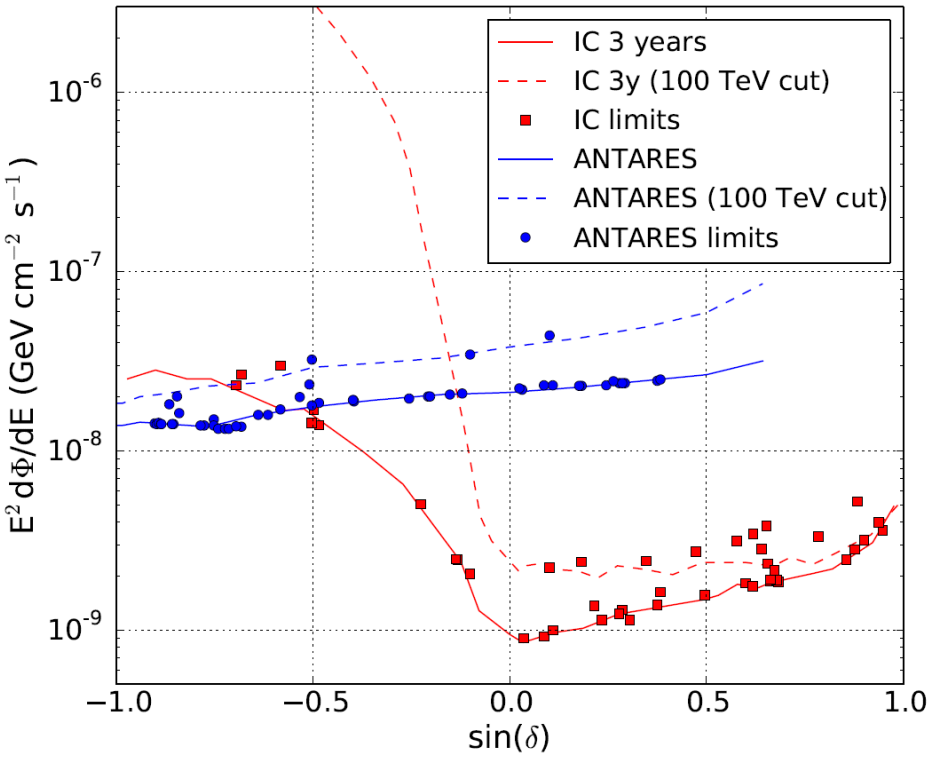
Neutrino astronomy in the Mediterranean Sea: ANTARES and KM3NeT

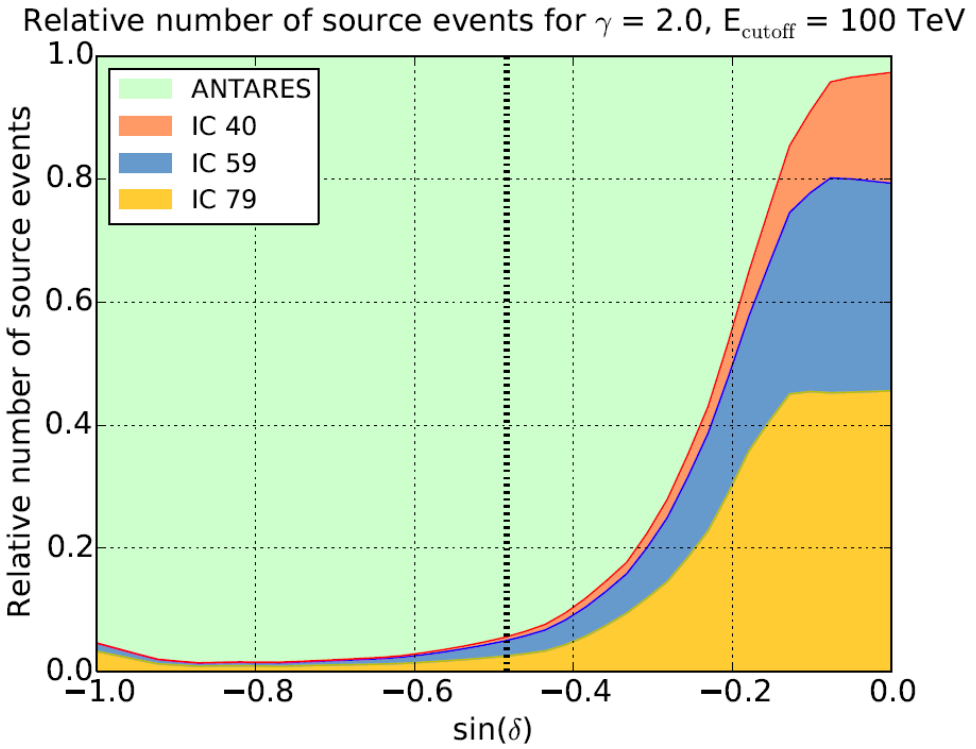
ANTARES: The first deep-sea ν telescope



- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- Proof of principle of deep-sea ν telescope
- Lots of results – but (too) small for cosmic neutrinos

ANTARES and IceCube: Combined analysis





- Common analysis of ANTARES and IceCube data
- Search for point-like neutrino sources, spectrum ~ $E^{-\gamma}$ * cutoff(E_{cutoff})
- Substantial contribution from ANTARES for spectra with E_{cutoff} ~ 100 TeV

The KM3NeT concept

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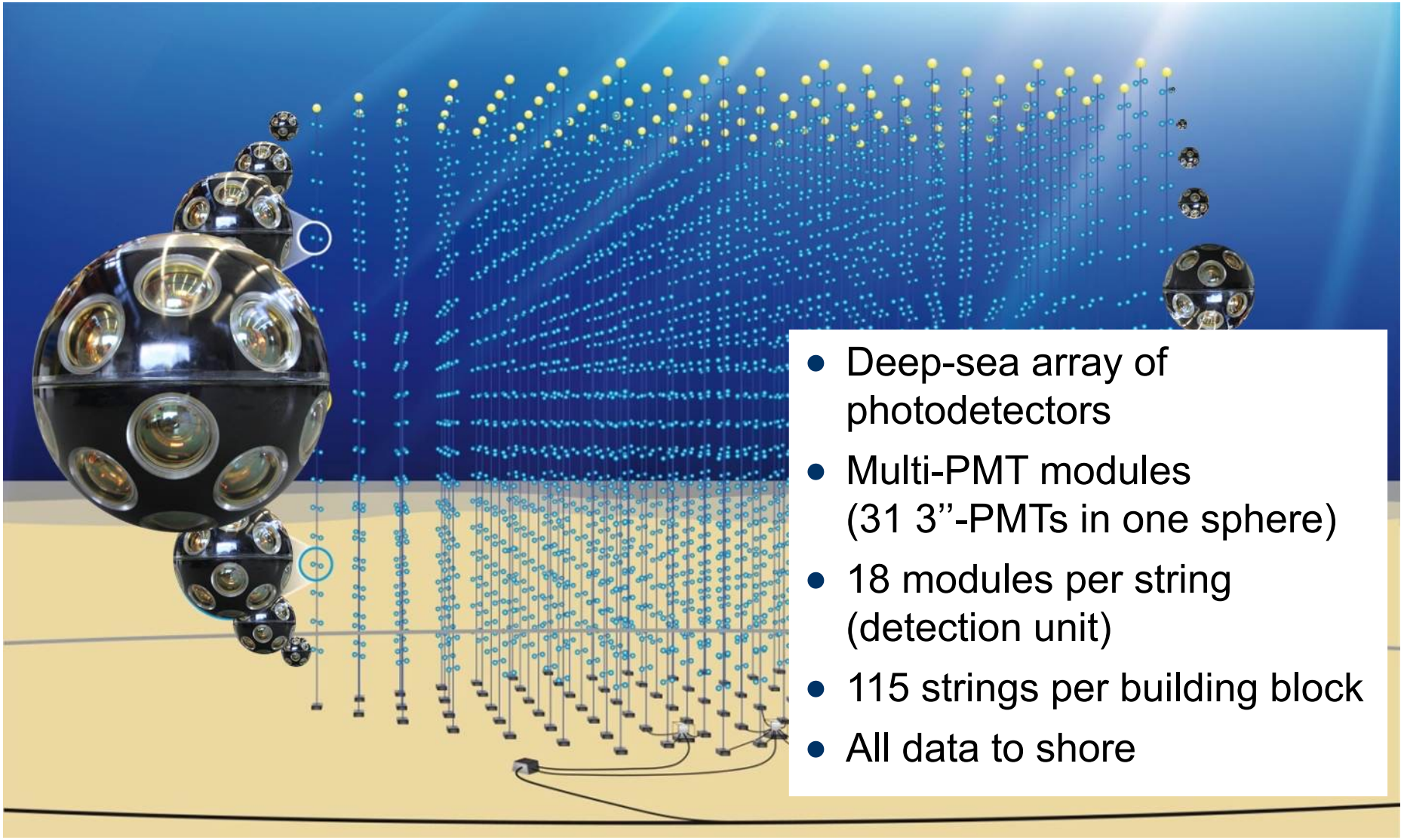
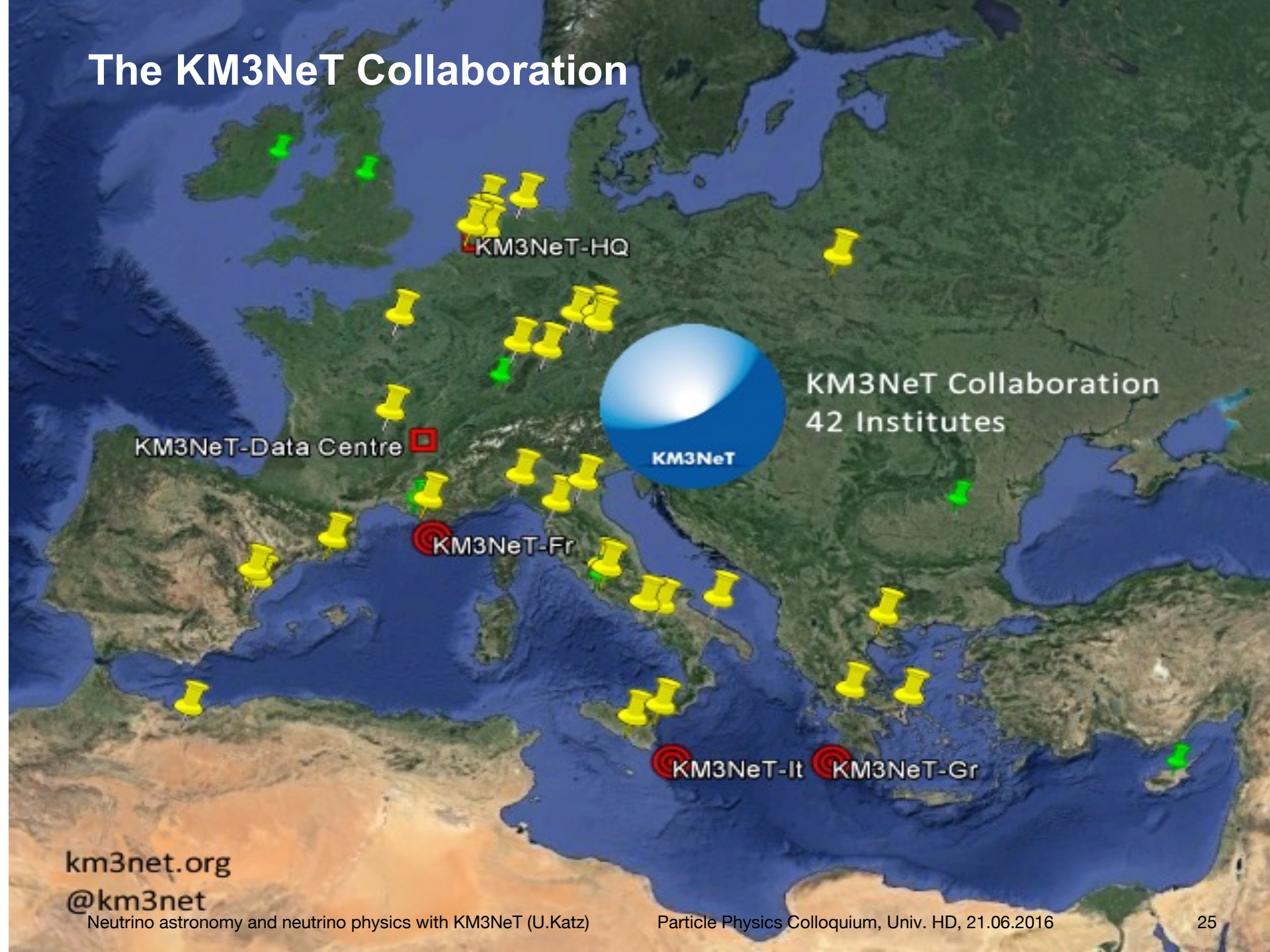


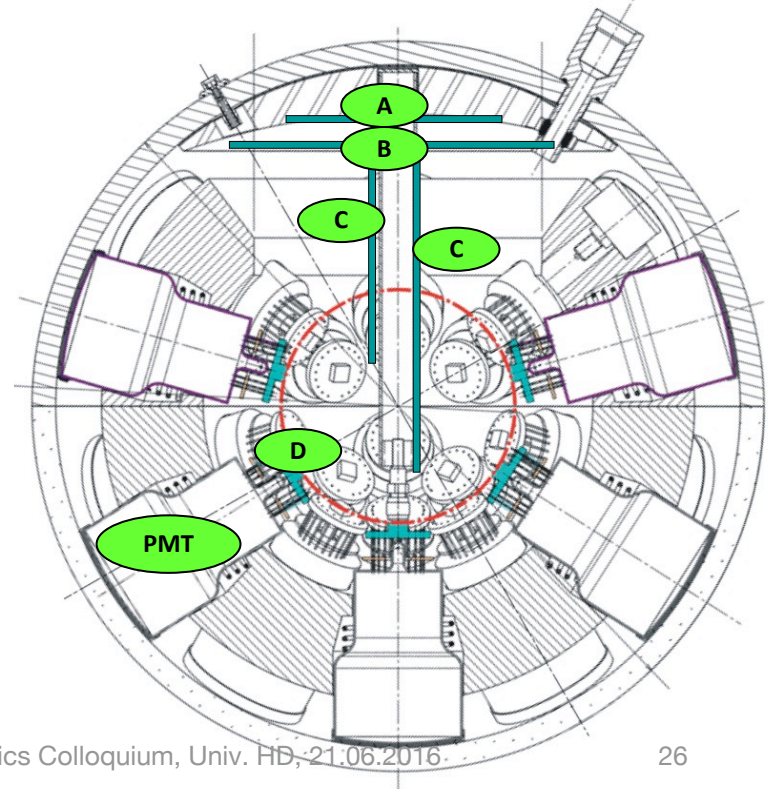
- Deep-sea array of photodetectors
- Multi-PMT modules (31 3”-PMTs in one sphere)
- 18 modules per string (detection unit)
- 115 strings per building block
- All data to shore

The KM3NeT Collaboration



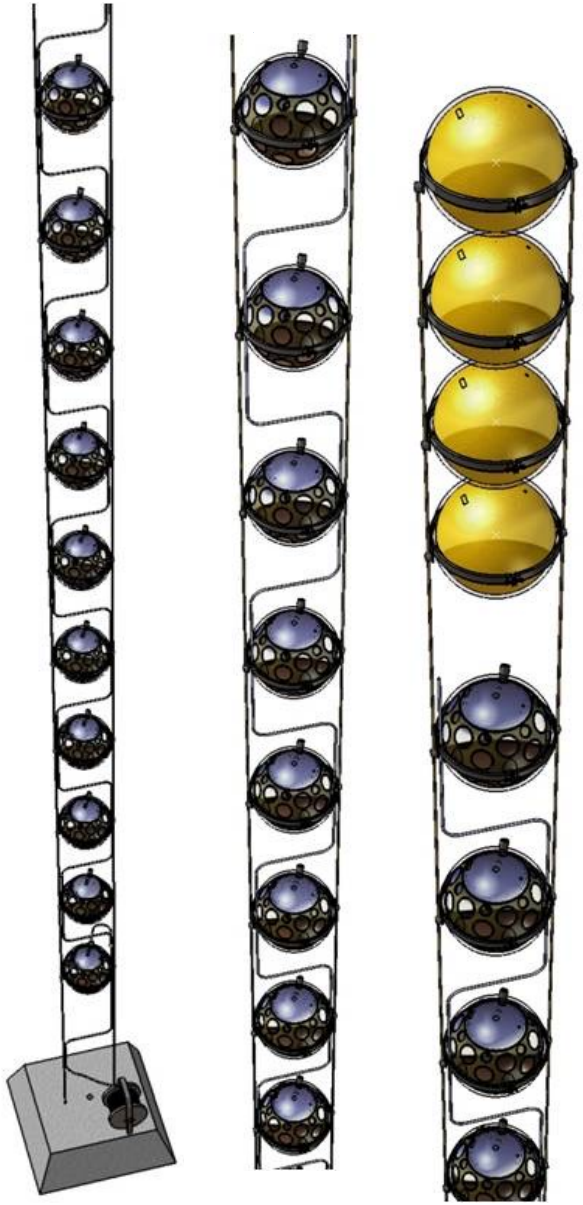
The KM3NeT Digital Optical Module

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10-inch PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk

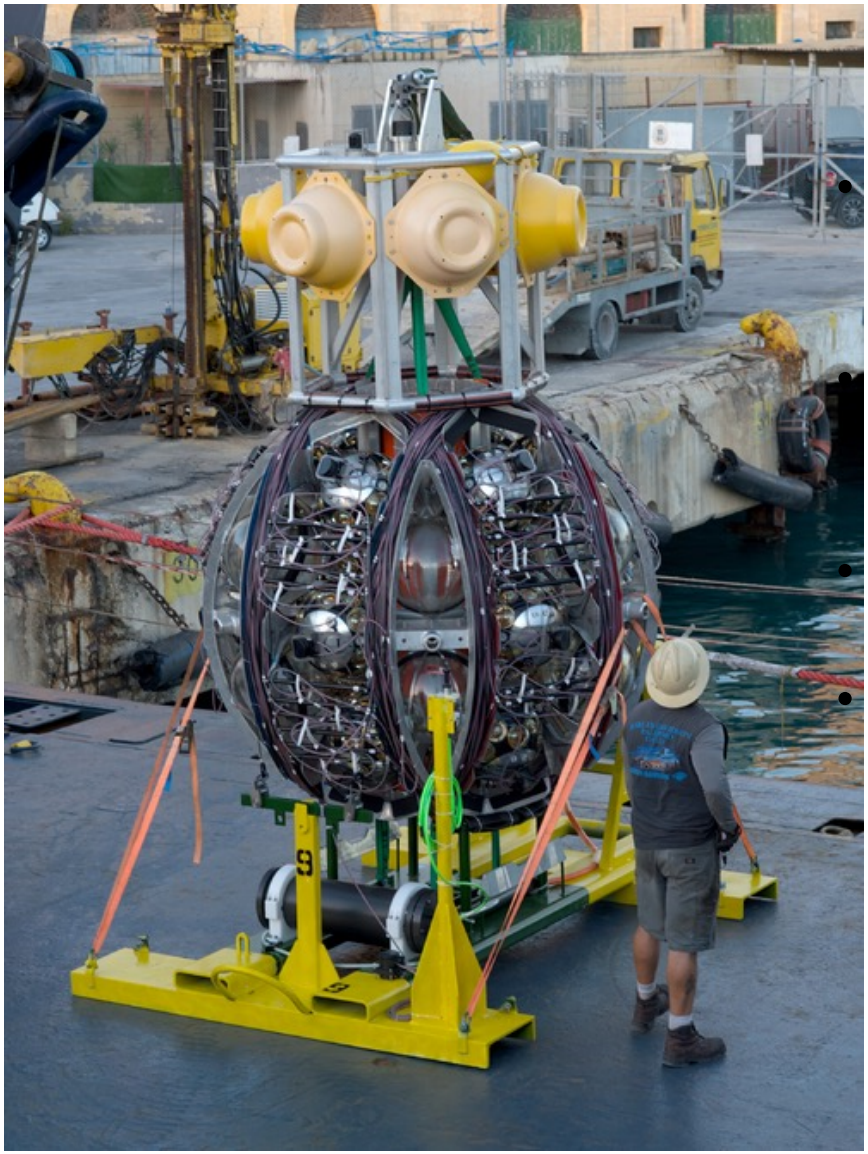


The KM3NeT detection unit (DU)

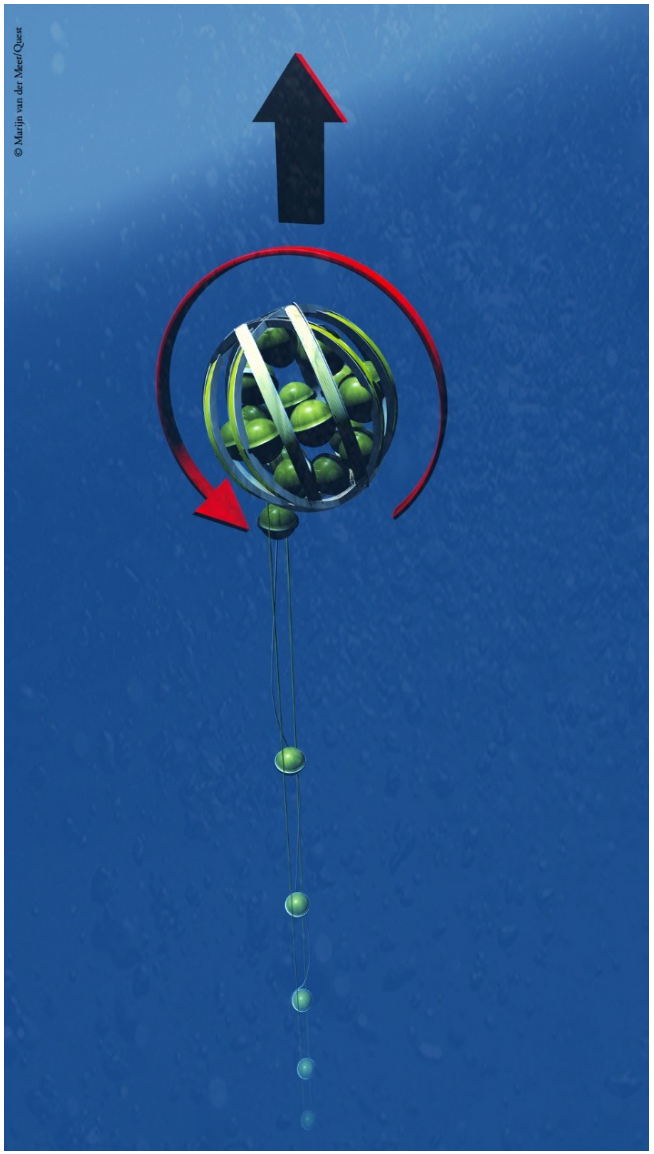
- Mooring line:
  - Buoy (empty spheres)
  - 2 pre-stretched Dyneema© ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 7mm diameter
  - Oil-filled
  - Optical fibres and copper wires
  - At each storey: Break-out box for connection to 1 fibre + 2 wires (one single pressure transition)



Deployment



- ← Deploy to sea bed
- Release by ROV
- Unfurl →
- Collect frame



The building block concept

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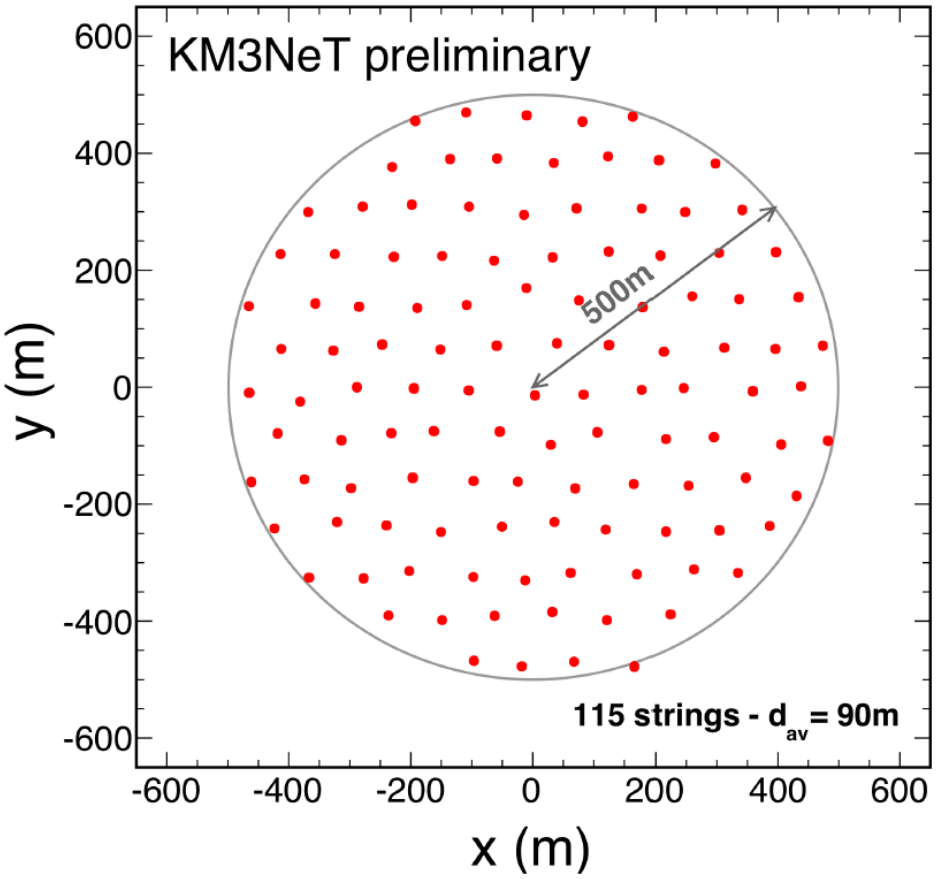
- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
- Large block (neutrino astronomy)
  - Sensitivity per string for muons independent of block size above ~75 strings
  - One block ~ half IceCube
- Small block (neutrino oscillations)
  - Precision measurement of atmospheric neutrinos
  - One block ~ 6 Mtons
- Allows for staged, block-wise, multi-site installation

DU distance adjusted to scientific objective:
90-120 m for neutrino astronomy /
20 m for oscillation research



KM3NeT 2.0 = ARCA and ORCA

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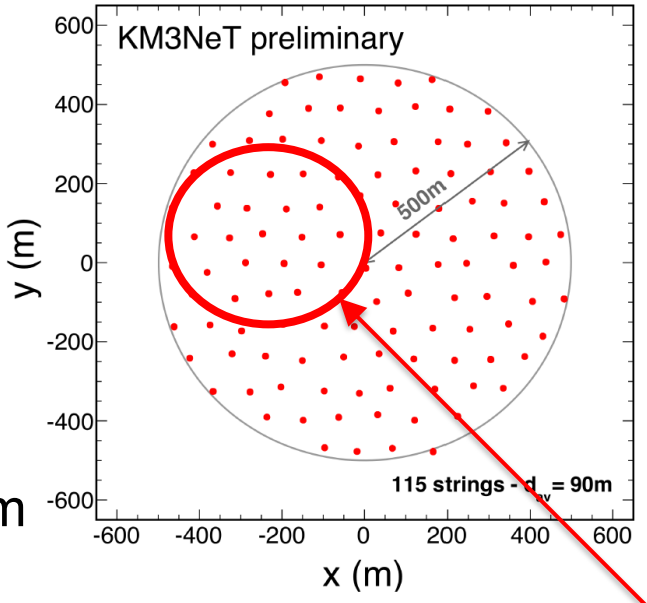
ARCA =

Astroparticle Research with Cosmics in the Abyss

Vertical DOM distance = 36 m



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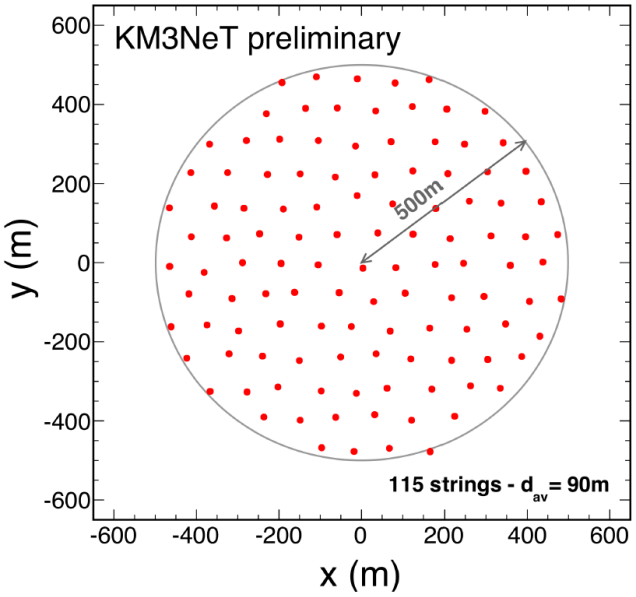
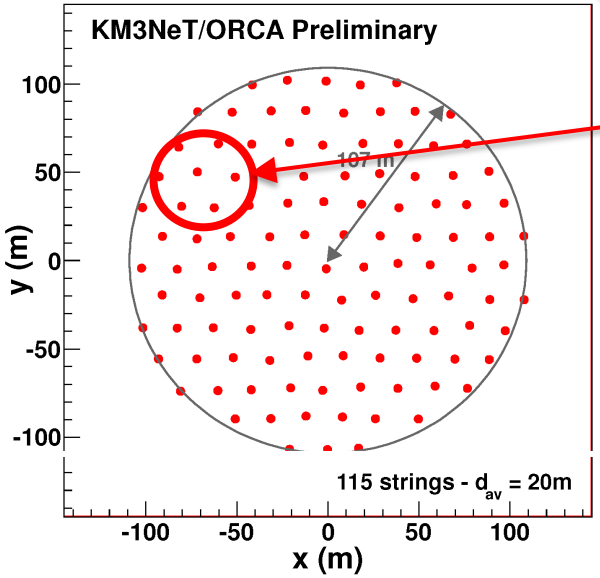


ORCA =

Oscillation Research with Cosmics in the Abyss

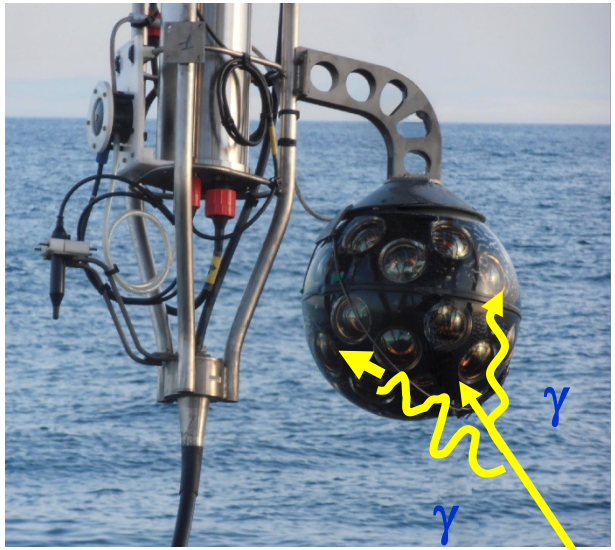
Vertical DOM distance = 9 m



Phase1 (fully funded)

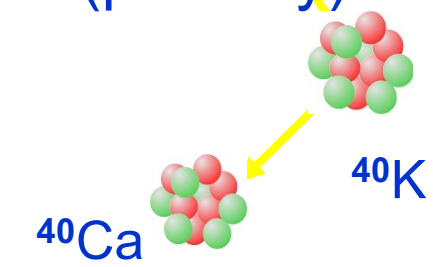
KM3NeT 2.0 Letter of Intent:
arXiv:1601.07459
to appear in J.Phys.G

DOM prototype (PPM-DOM)

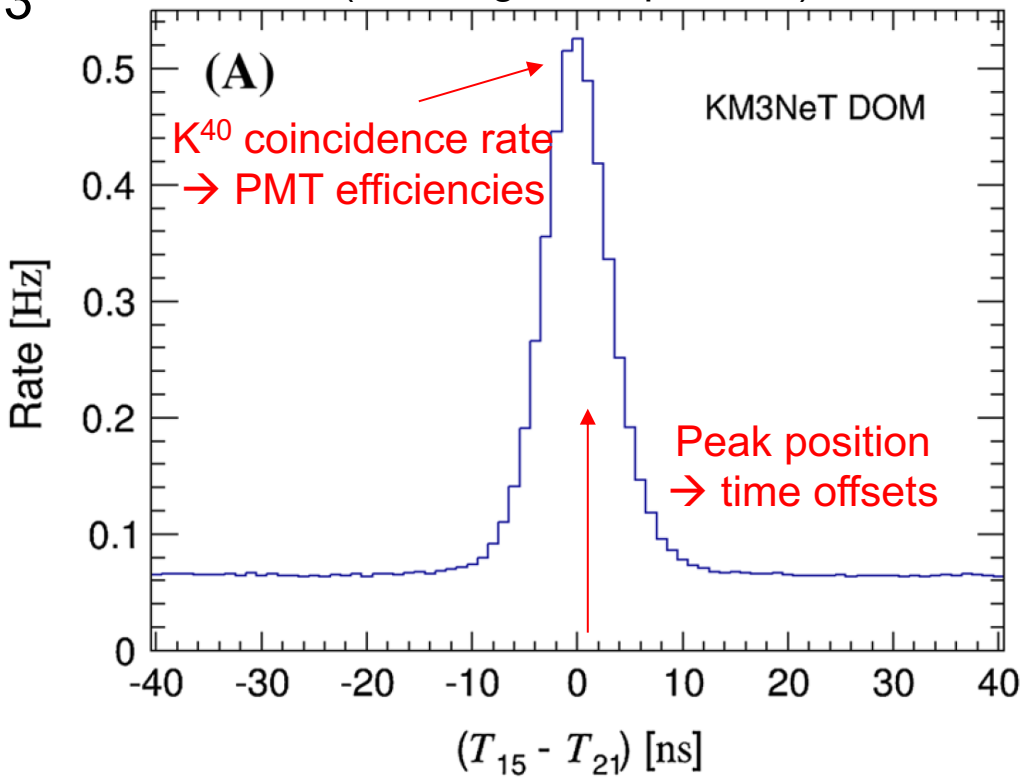


Deployed at ANTARES in April 2013

Up to 150 Cherenkov photons per decay



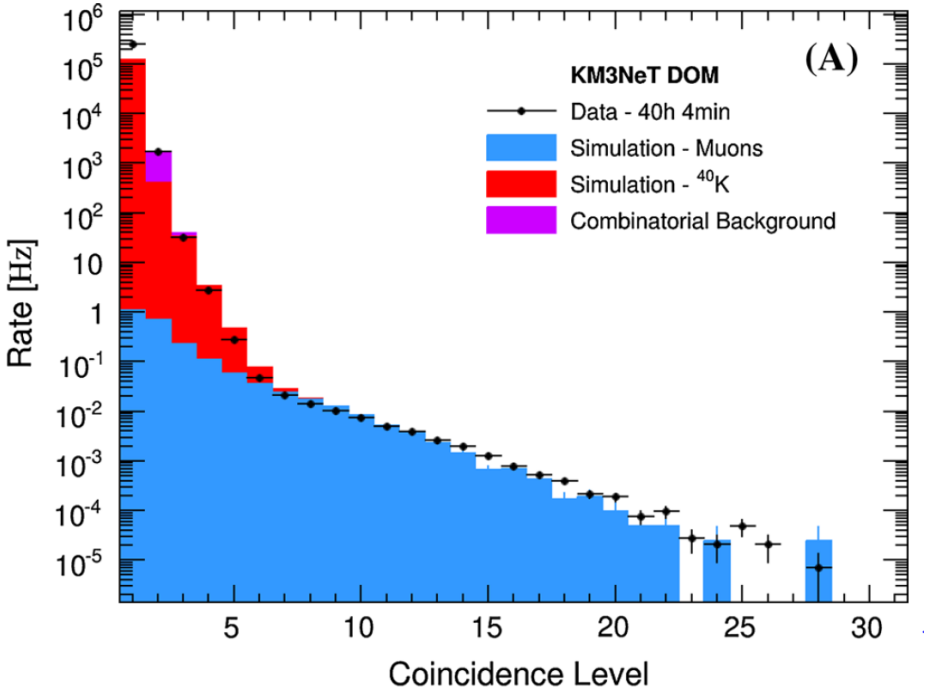
Coincidence rate on 2 adjacent PMTs (33° angular separation)



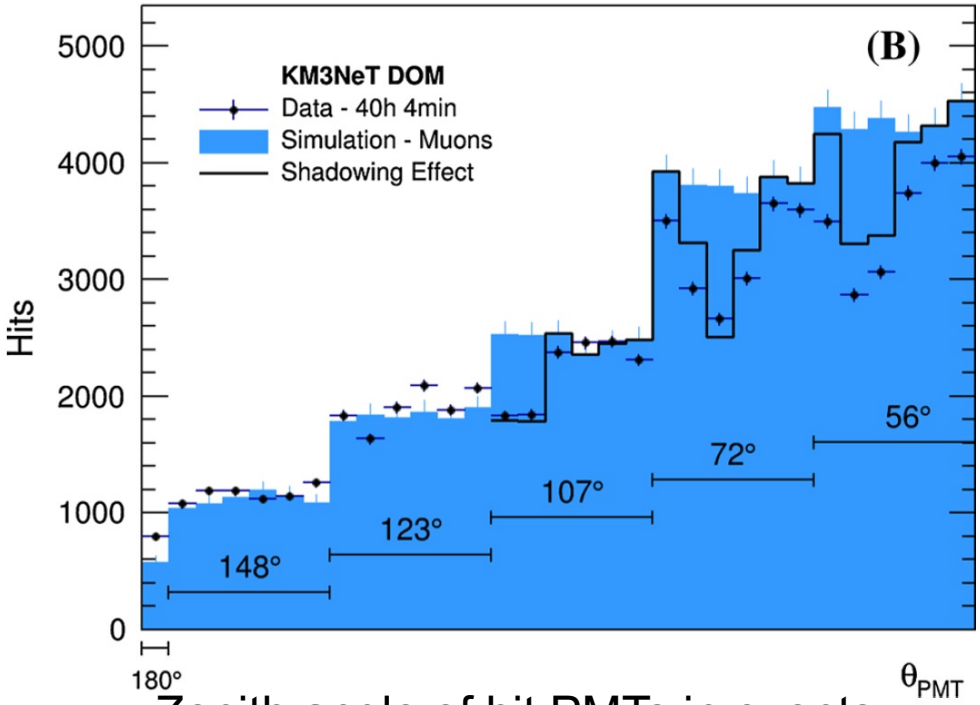
Concentration of ^{40}K is stable (coincidence rate ~5 Hz on adjacent PMTs)

Eur.Phys.J. C74 (2014) 3056

PPM-DOM: Atmospheric muons



Number of coincident hits in a DOM



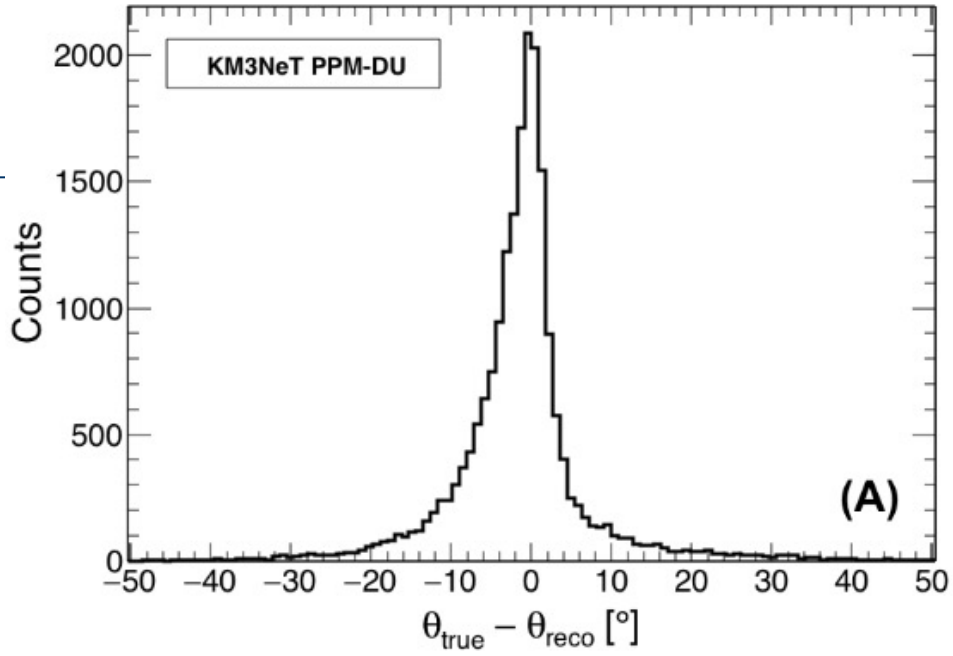
Zenith angle of hit PMTs in events with more than 7 coincident hits

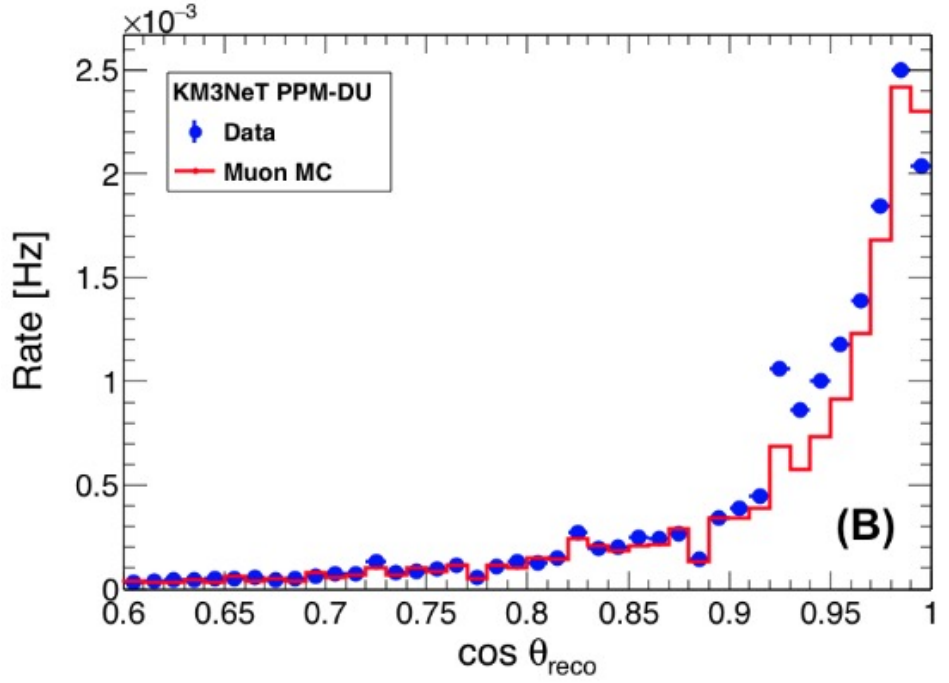
>5 coincidences within 20ns ⇒ reduced K40 contribution, dominated by atmospheric muons

More upper PMTs in multi-hit events ⇒ directional information from single storey

PPM-DU: Muon reconstruction

- Reconstruct muon trajectory from hits on 3 DOMs
- Ambiguities can be reduced by cuts on time differences
- 7° FWHM resolution achieved





Eur.Phys.J. C76 (2016) 54

First KM3NeT-ARCA strings deployed

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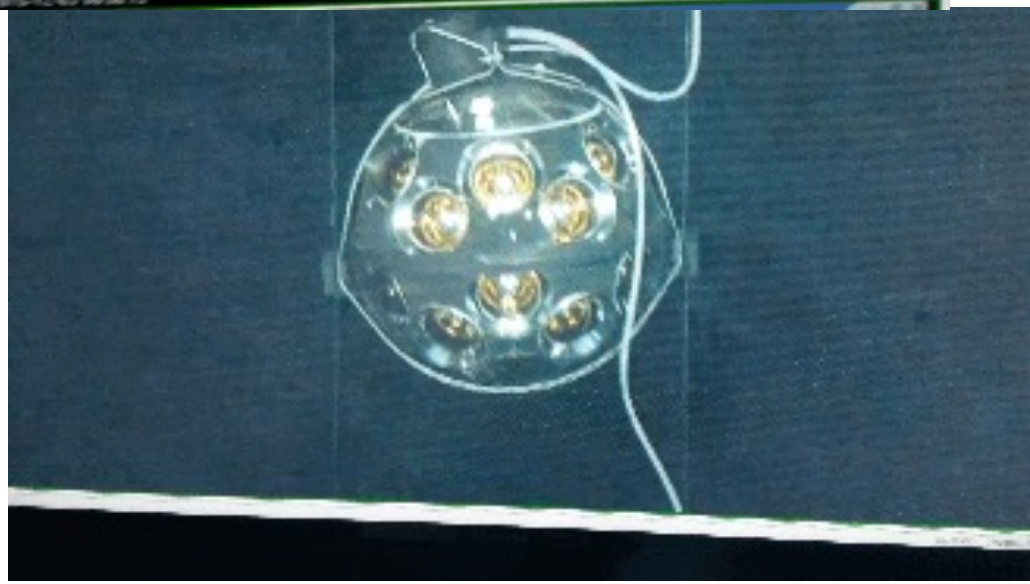
First string (Dec 2015)

- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress

Strings #2 and #3 (May 2016)

- String #2: 16/18 DOMs work, data taking in progress
- String #3: Short in power system, not operational
- Problems under investigation



First neutrinos …

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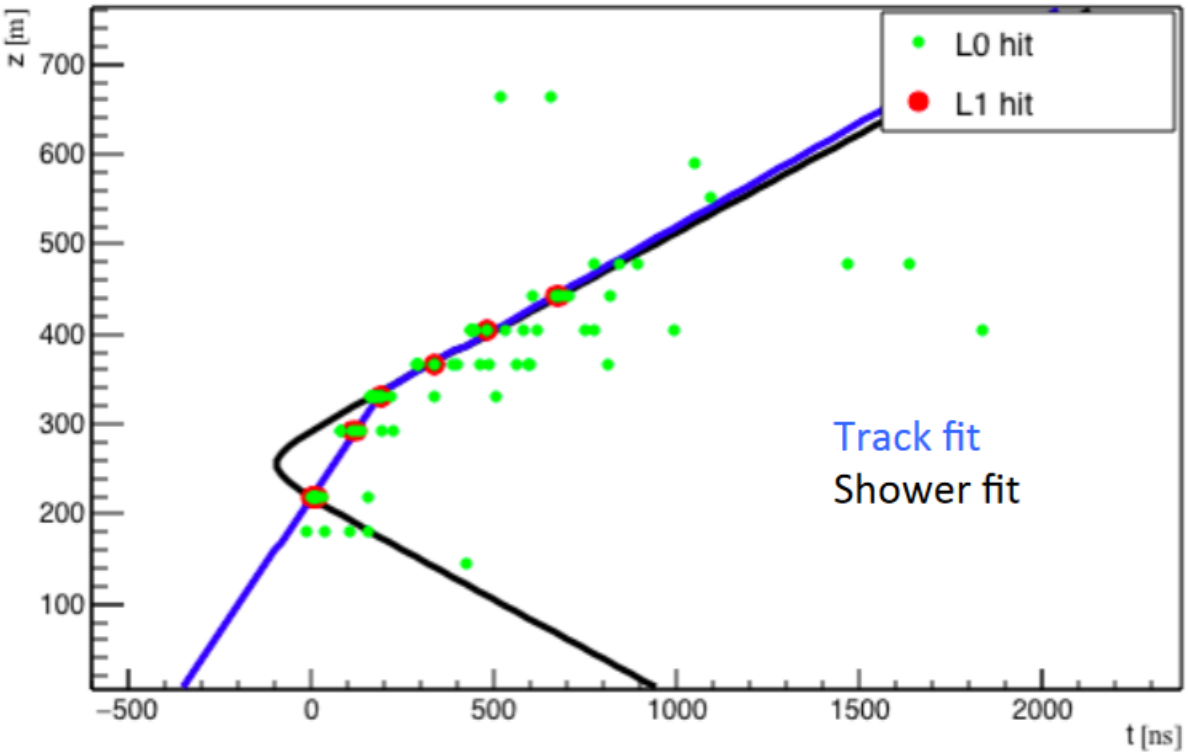
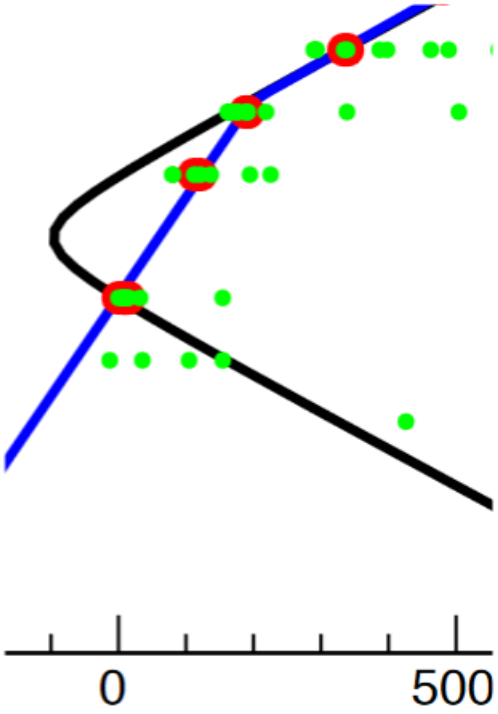
A good candidate:

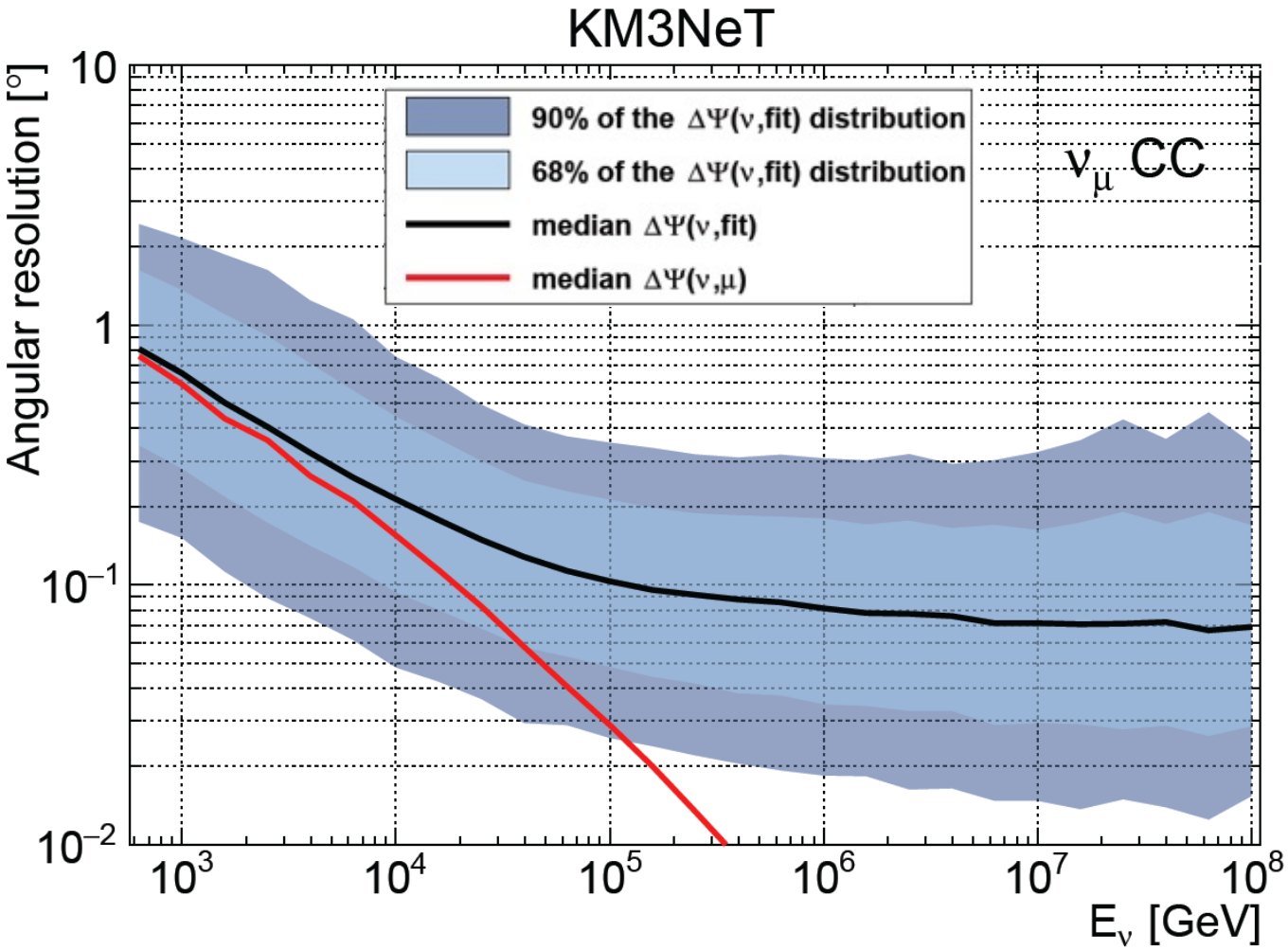




Note: Track direction from slope, rising z(t) not sufficient

Muon angular reconstruction

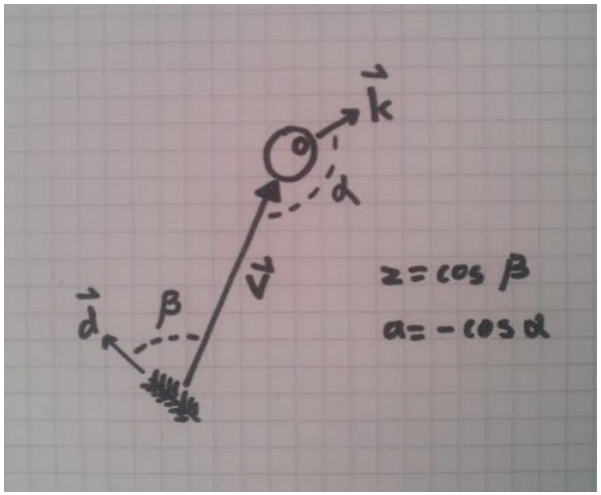
Reconstruction using new PMT response simulation:
Median of angle $\Delta\Omega$ between reconstructed μ and true ν direction



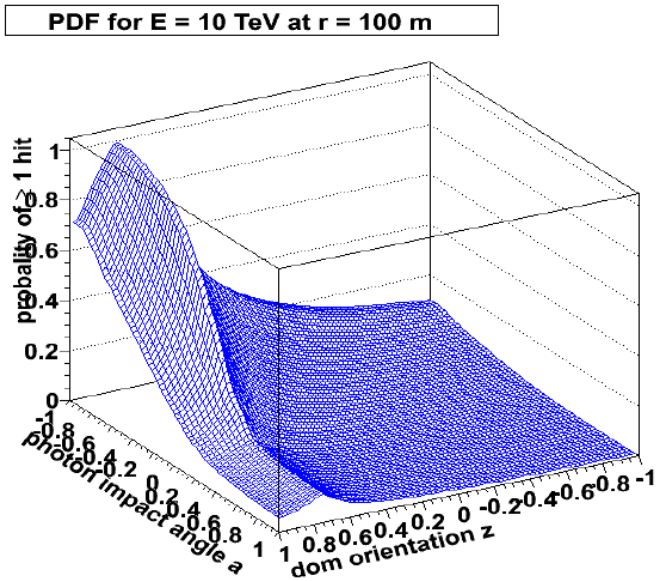
0.07°

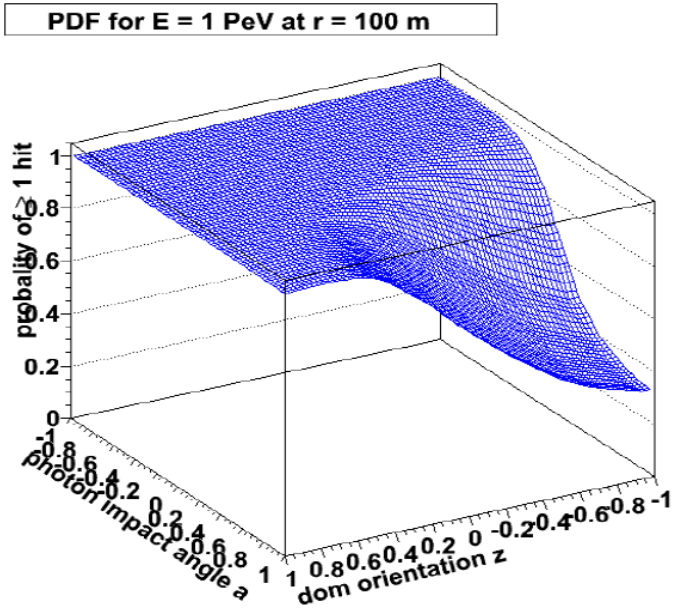
Shower reconstruction: Method

- Vertex fit: Suitable hit selection, fit uses timing; result used for containment requirement
- Direction and energy: Uses PDF depending on
  - Distance vertex – DOM
  - Angle between shower direction and DOM
  - Orientation of PMTs
  - Hit information used: yes/no



- Resolution (contained ν_e CC events): ~10% in E, <2° in direction



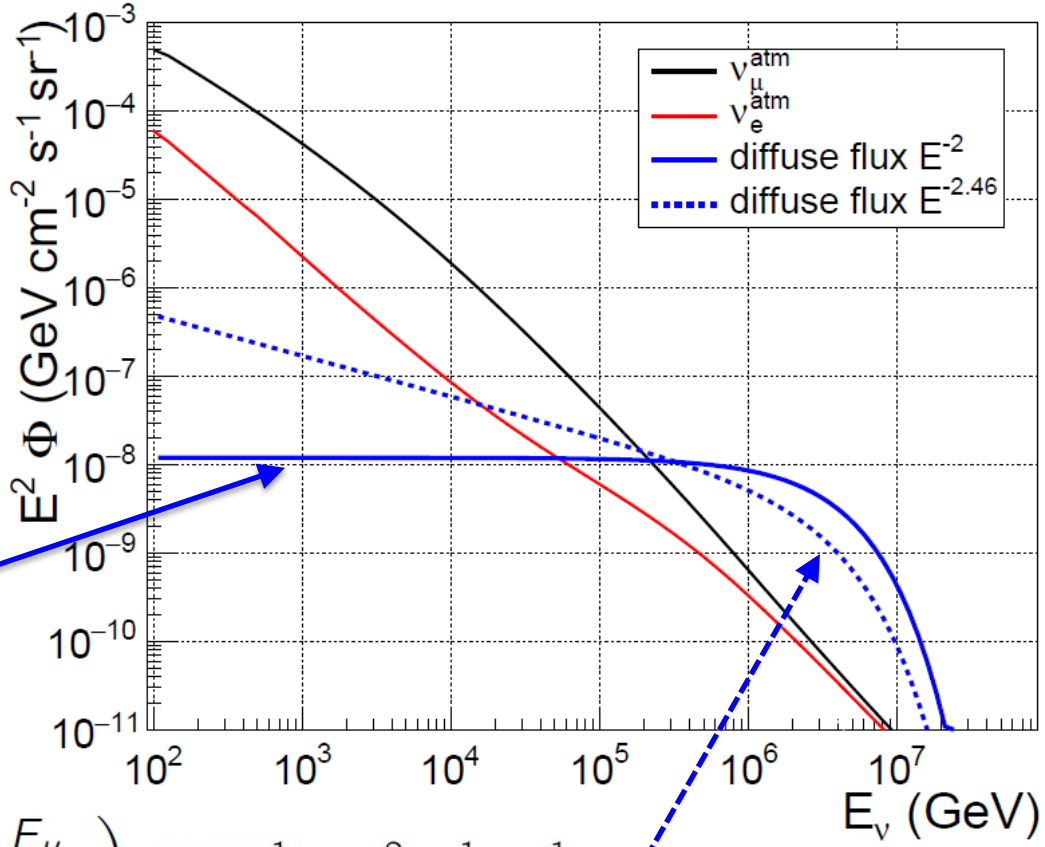


Diffuse extragalactic neutrino flux

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Assumptions:

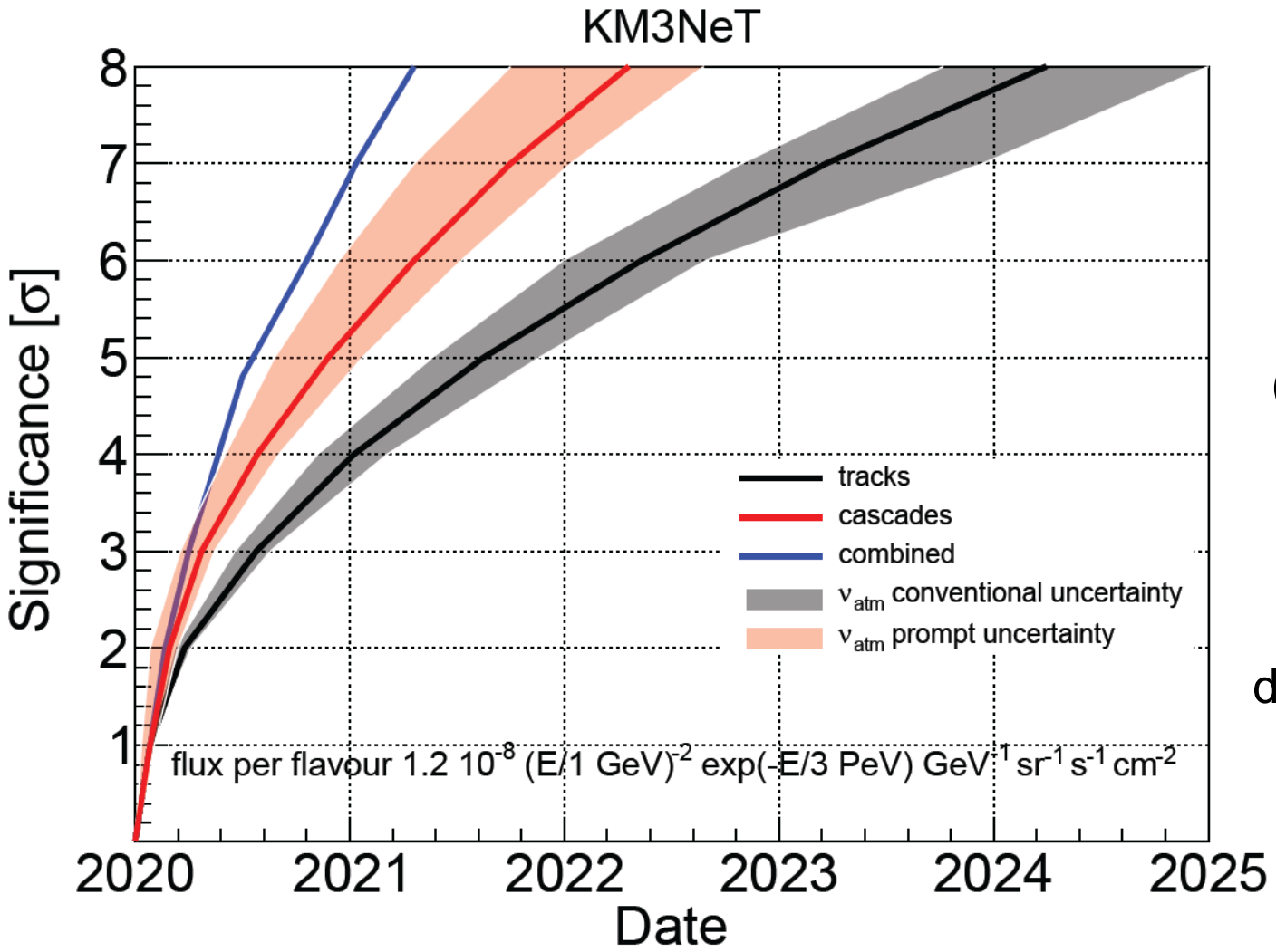
1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings



$$\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.46} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Diffuse flux results (max. liklihood)



Event numbers (cut&count):

16/9 cascades

7.5/5 track-like

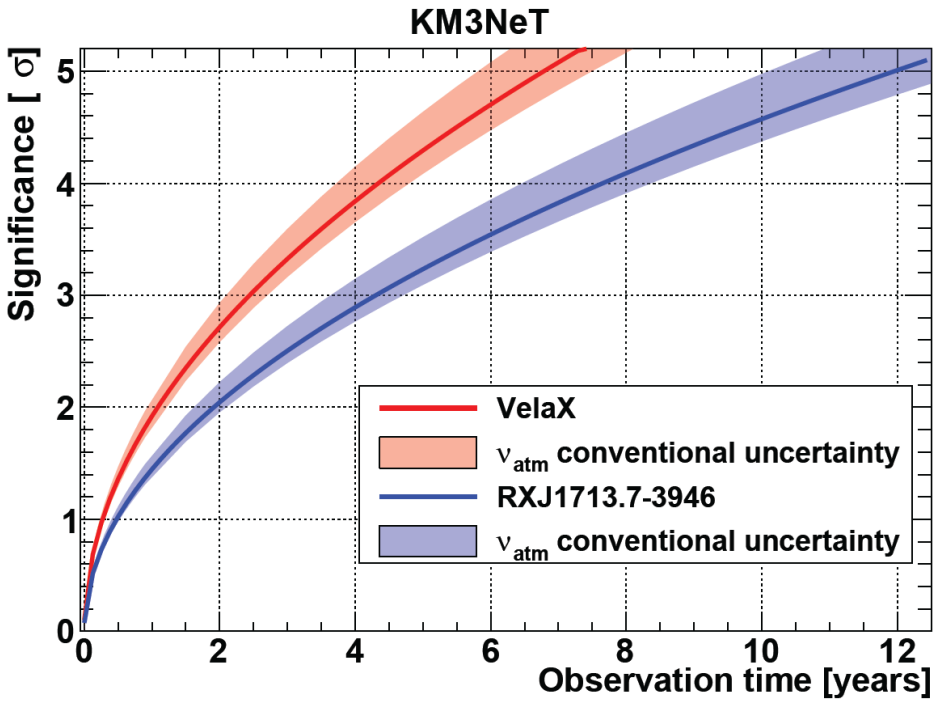
(signal/background per ARCA year)

Note:

For each energy, direction and flavour, KM3NeT is complementary to IceCube

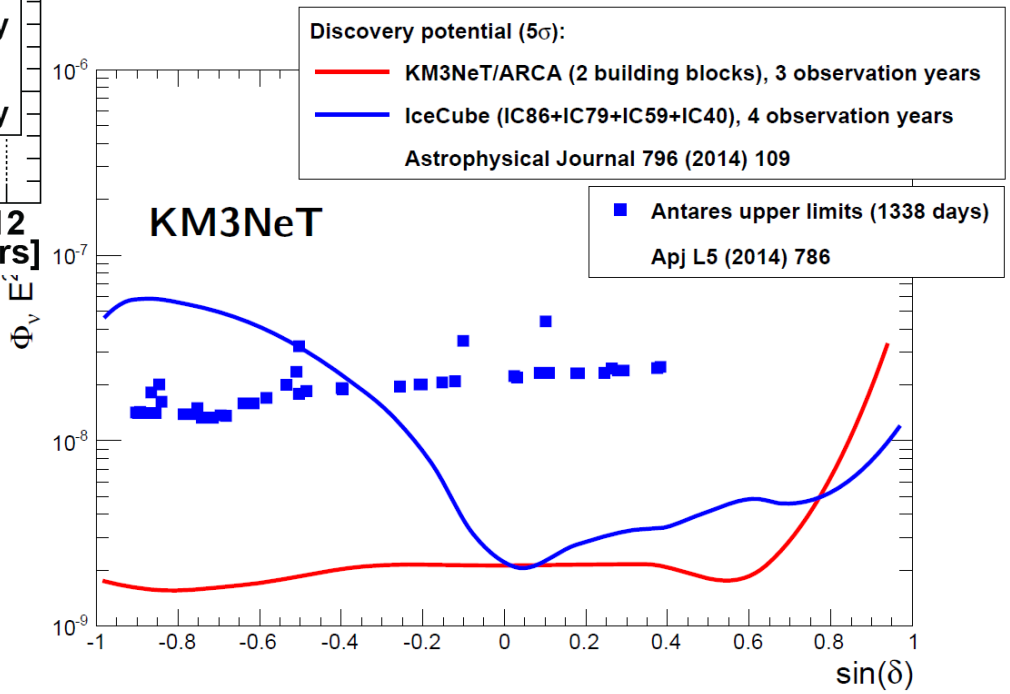
Other flux assumptions yield 10-30% improvement in discovery time.

Point-source results



- Galactic sources in reach

- Significant discovery potential for extragalactic sources



Measuring the neutrino mass hierarchy

Neutrino oscillations in vacuum

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Neutrino flavour and mass eigenstates are not the same:

$$\underset{\text{(propagation)}}{[\text{mass}] \rightarrow} \quad |\nu_i\rangle = \sum_{\alpha=1}^{3} U_{i\alpha}|\nu_\alpha\rangle \quad \underset{\text{(production)}}{\leftarrow [\text{flavour}]}$$

- Consequence: Neutrino oscillations
  Very simplified case: 2 flavours, vacuum

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2/\text{eV}^2 \cdot L/\text{km}}{E_\nu/\text{GeV}}\right)$$

- No information on sign of Δm^2

- In the above units:

$L/E \ll 1/\Delta m^2 \quad \rightarrow$ no effect
$L/E \sim 1/\Delta m^2 \quad \rightarrow$ observe oscillations
$L/E \gg 1/\Delta m^2 \quad \rightarrow$ observe averaged oscillations

The 3-flavour case

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Parameterisation of mixing matrix
  (up to Majorana phases that are not discussed here):

$$U_{\mathrm{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

  with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

- Neutrino oscillation parameters (only central values given):

$\sin^2(2\theta_{23}) = 0.97; \quad |\Delta m^2_{23}| = 2.35 \times 10^{-3}\,\mathrm{eV}^2$ atmos. + acc.

$\sin^2(2\theta_{12}) = 0.86; \quad \Delta m^2_{12} = 7.58 \times 10^{-5}\,\mathrm{eV}^2$ solar + reactor

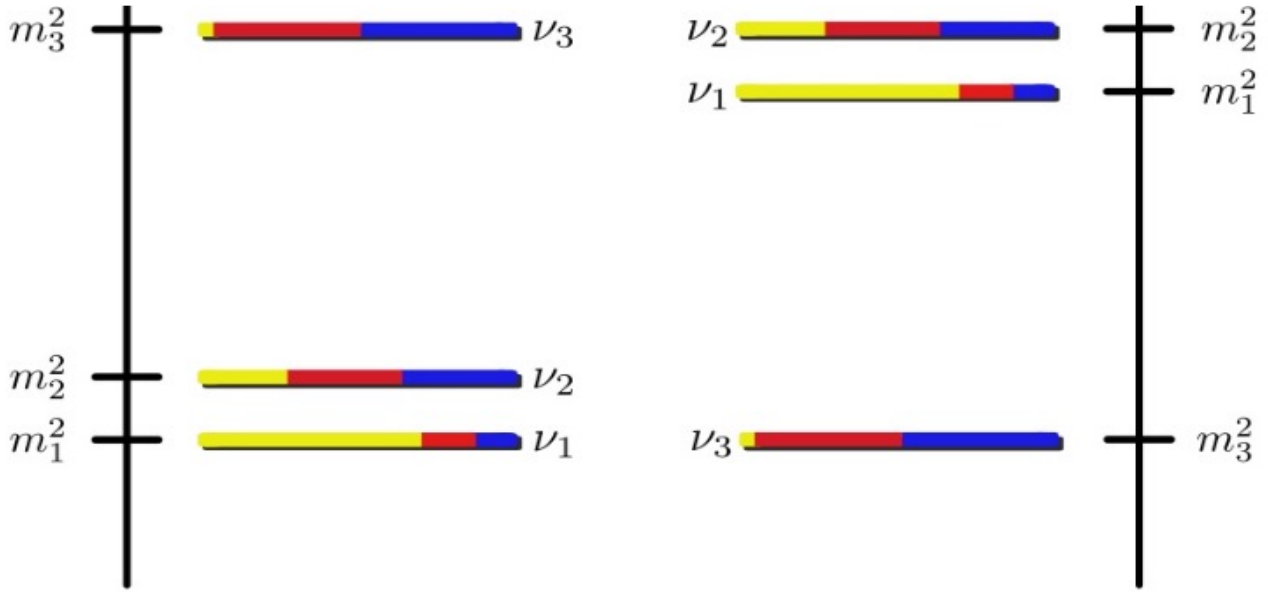
$\sin^2(2\theta_{13}) = 0.096;$ reactor (2012)

- Unknown: sign of Δm^2_{23}
  CP-violating phase δ

The neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :

"normal hierarchy" (NH) or "inverted hierarchy" (IH)



- A fundamental parameter of particle physics!
  → Knowledge required to investigate neutrino CP violation
  → Important also for cosmology

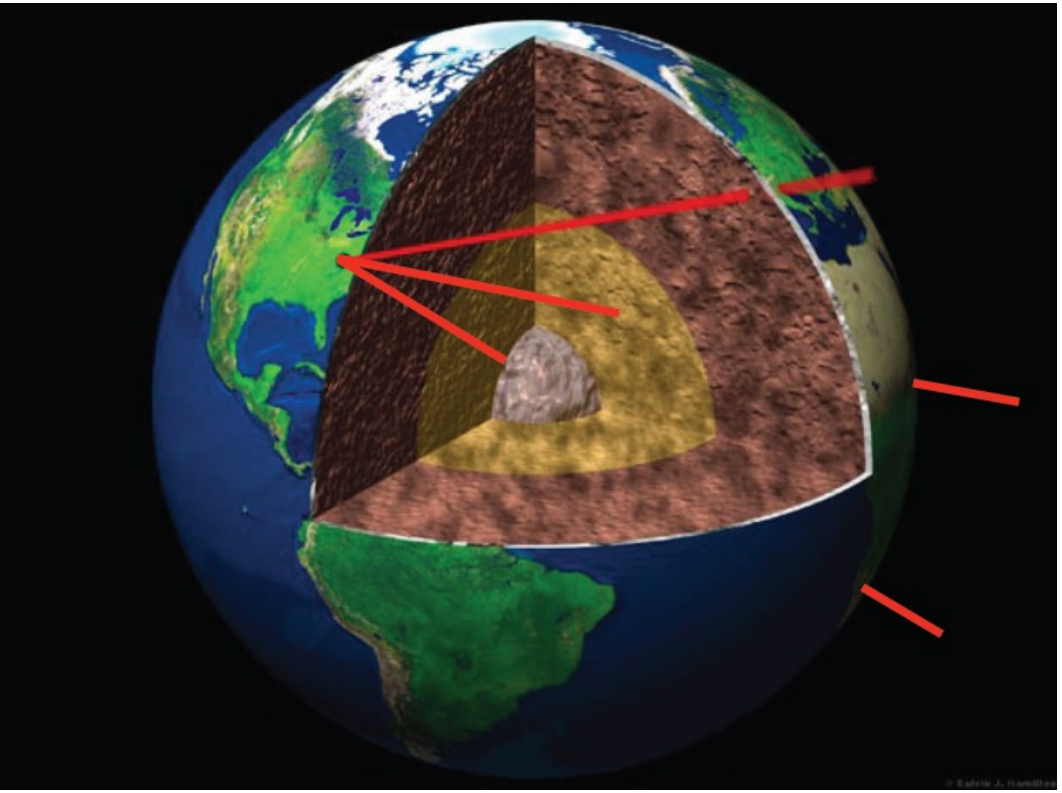
Neutrino oscillations in matter

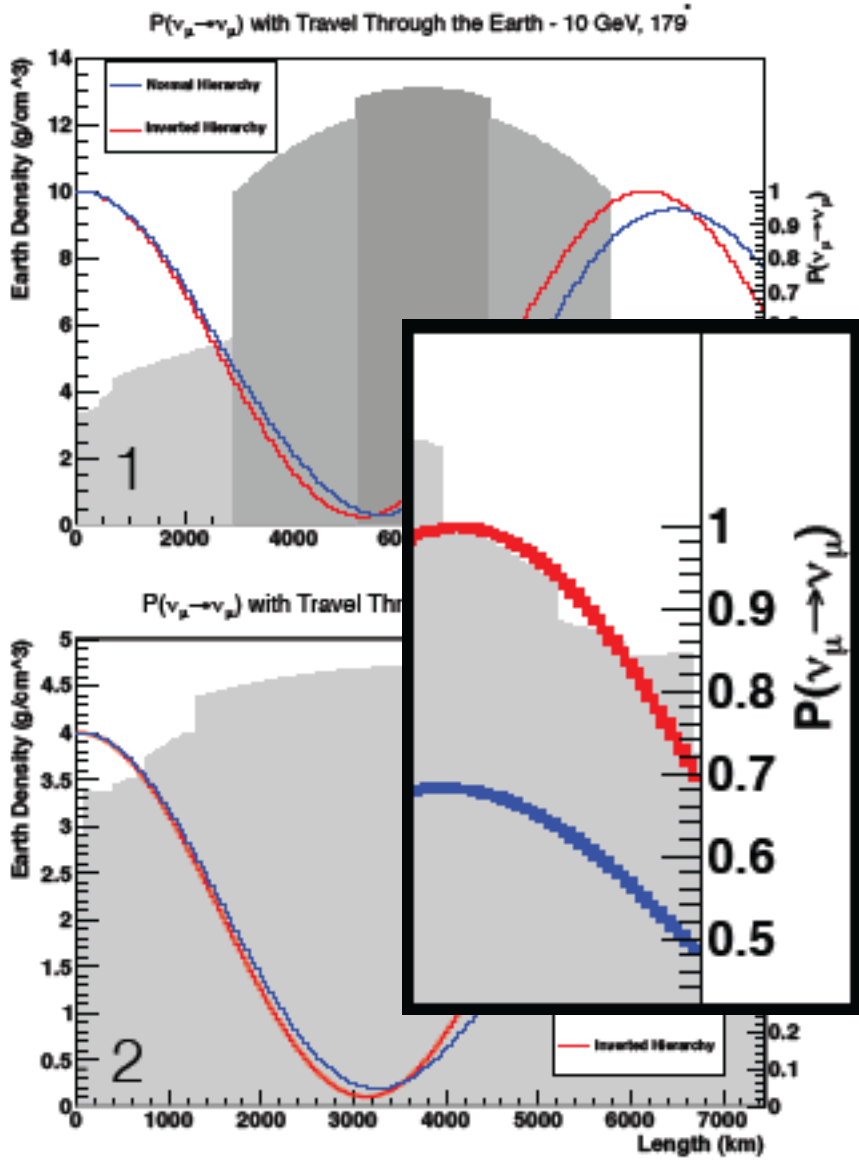
- Electron density induces dependence of oscillation pattern on sign of Δm^2_{23}
- Effect equal for neutrinos/NH and antineutrinos/IH
- Oscillation in Earth “just perfect” if E_ν = few GeV
- Measurable using atmospheric neutrinos because
  - Less antineutrinos than neutrinos in atmospheric flux
  - σ(antineutrino+N) < σ(neutrino+N)

Neutrino oscillations in the Earth

Earth density 4-13 g/cm^3 →

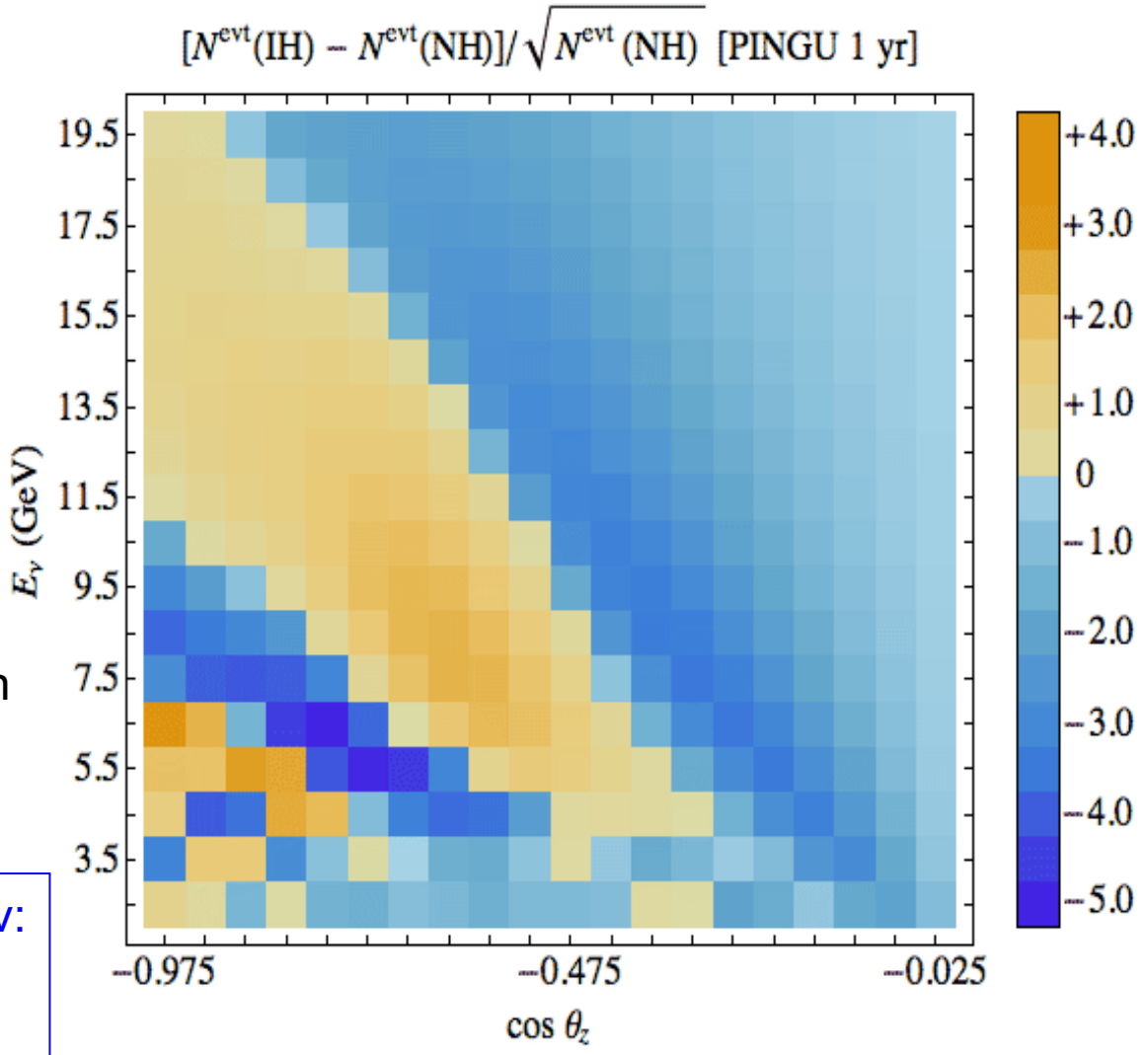
Relevant: $E_\nu \sim 3\text{–}10\ \mathrm{GeV}$





Mass hierarchy “oscillogram”

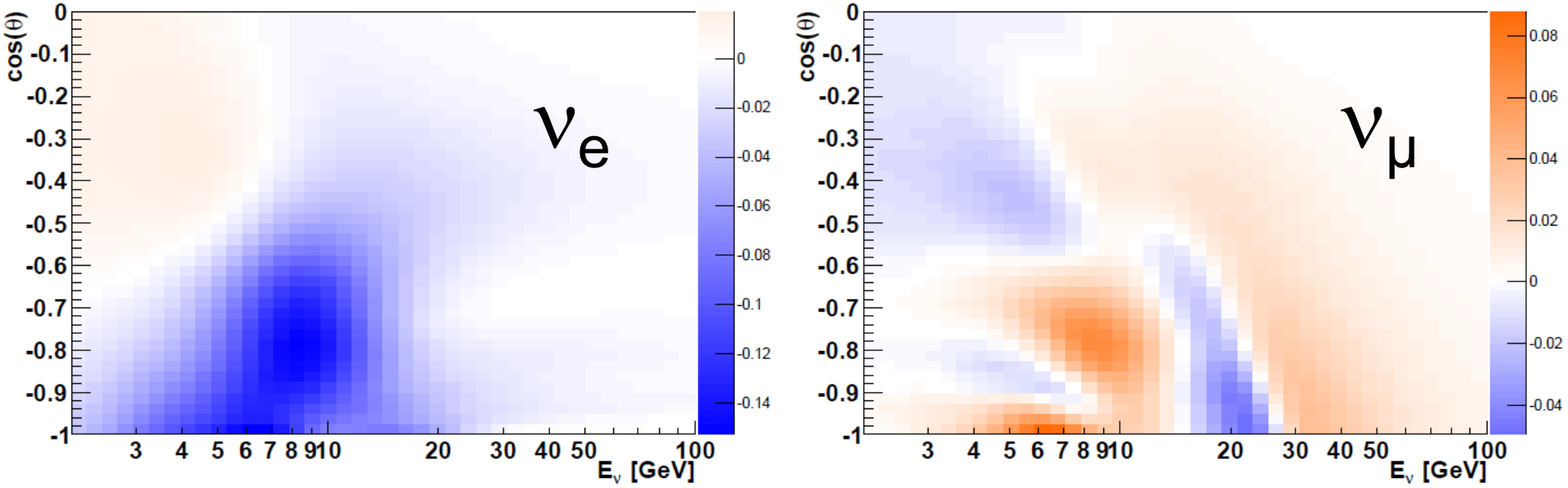
- Expected signal significance in energy vs. zenith w/o experimental effects
- Need to assess neutrino reactions at 3–20 GeV
- Required:
  - Good angular and energy resolution
  - Flavour separation



Akhmedov, Razzaque, Smirnov: JHEP 1302 (2013) 082, JHEP 1307 (2013) 026

… and in the real world

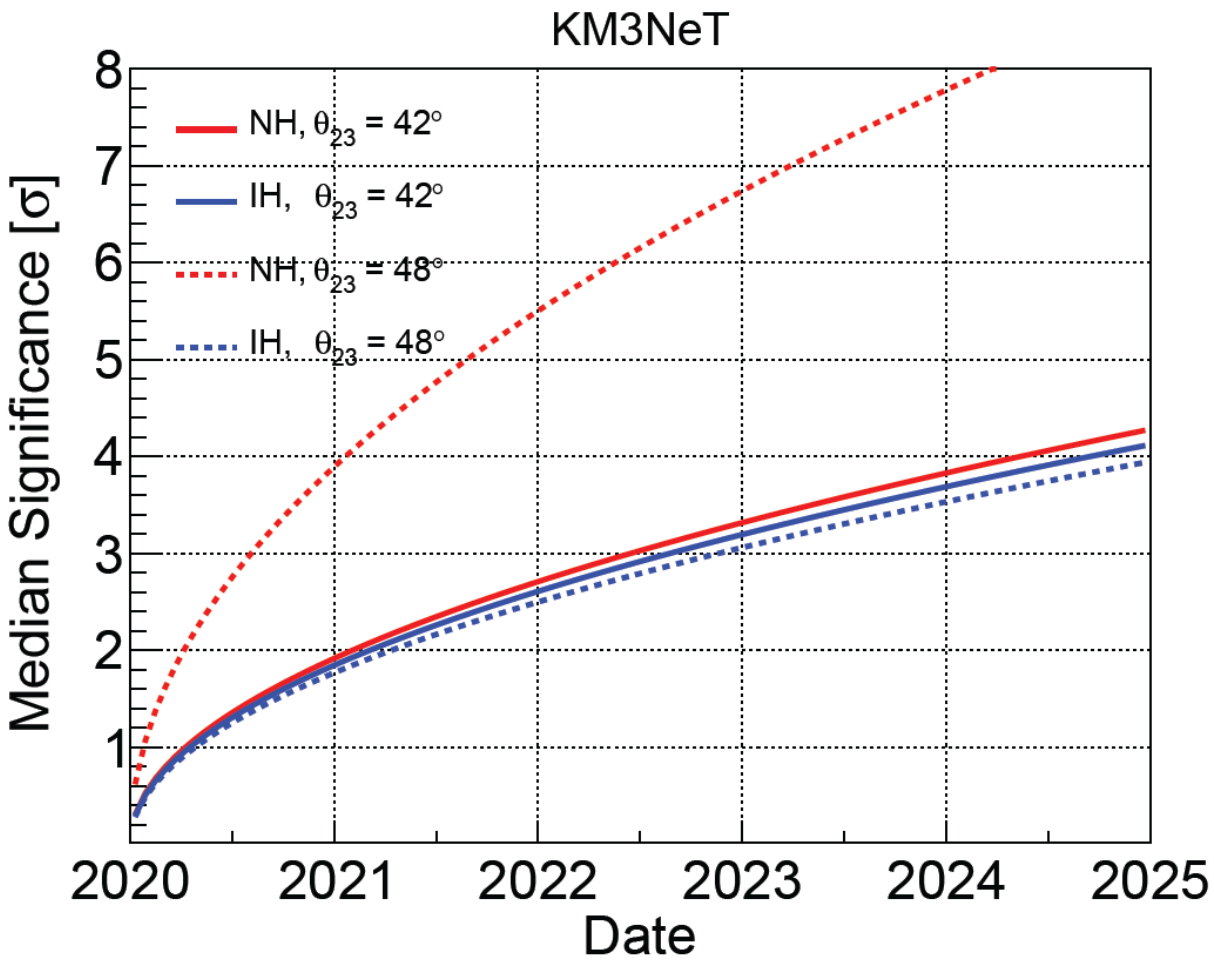
$$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$$



- Both muon (ν_μ survival) and electron channel ($\nu_\mu \rightarrow \nu_e$ conversion) contribute
- Removal of atmospheric muon background essential
- Major effort to control systematics
- But: Measurement in reach

Measuring the mass hierarchy

- Sensitivity depends on true value of θ_{23} (“the octant”)
- CP phase δ=0 assumed
- 3σ in 3 years for most unfavourable situation
- Similar result for PINGU, but later starting date



Summary and outlook

- Neutrino astronomy has become mature – transition from searches to observation
- Addressing fundamental questions of particle and astrophysics, and of cosmology
- Cubic-kilometre detectors required for astrophysical observations
- Full sky coverage by IceCube and KM3NeT, complementary environments and sensitivities
- Neutrino mass hierarchy in reach within 10 years

Stay tuned!